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I/O-INTENSIVE EMBEDDED SYSTEMS: THE INFOPIPE APPROACH

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14. ABSTRACT

Infopipes are a distributed computational and communications abstraction for information flow applications and I/O intensive distributed real-time embedded (DRE) systems. Infopipes are specified by the syntax, semantics, and quality of service requirements for information flows. Software tools generate executable code from the specification. Building applications that process information flows on existing middleware platforms is difficult, because of the variety of QoS requirements, the need for application-specific protocols, and the poor match of the commonly used abstraction of remote invocations to streaming. The ability to query individual Infopipe elements as well as composite Infopipes for properties of supported flows enables QoS-aware configuration. Similar to local protocol frameworks, Infopipes provide a flexible infrastructure for configuring communication services from modules, but unlike protocols the abstraction uniformly includes the entire pipeline from source to sink, possibly across process and node boundaries.

15. SUBJECT TERMS
infopipe, distributed real-time embedded systems, quality of service, information flow

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1 Purpose of Report

This final report summarizes the effort (the *Embedded Infopipe* project) expended by the Georgia Institute of Technology (GT) and Oregon Graduate Institute (OGI) teams in support of Wright-Patterson Air Force Base and DARPA on Contract F33615-00-C-3049, supported by the PCES program. This project is conducted in cooperation with the *Infosphere* project expended by the Oregon Graduate Institute (OGI) and Georgia Institute of Technology (GT) teams. Some of the results described in this report leverage on funding from other sources, which we will point out as appropriate.

2   Project Members

2.1   Embedded Infopipe Project

The faculty members and research scientists involved in the Embedded Infopipe project are:

- Prof. Calton Pu (PI, Georgia Institute of Technology)
- Prof. Mustaque Ahamad (Georgia Institute of Technology)
- Prof. Ling Liu (Georgia Institute of Technology)
- Prof. Karsten Schwan (Georgia Institute of Technology)
- Prof. Yannis Smaragdakis (Georgia Institute of Technology)
- Dr. Greg Eisenhauer (Georgia Institute of Technology)
- Mr. Wenchang Yan (Georgia Institute of Technology)
- Prof. Jonathan Walpole (Oregon Graduate Institute)

In addition, about 20 graduate students have received research assistantships from the project. One research staff member (Mr. Rick Sar of Georgia Institute of Technology) also contributed to the project.

3 Project Description

3.1 *Embedded Infopipe Project* (updated 10/01)

Overall Plan. The proposed project, in cooperation with Infosphere, consists of the PI plus three co-PIs and two participating faculty members. The main areas of research are Infopipe specialization and optimization for embedded systems, Infopipe adaptation and restructuring, and Infopipe data management in resource-constrained environments. Prof. Pu, Prof. Schwan, and Prof. Liu will lead these efforts, assisted by each other and Prof. Walpole in a consulting role. Prof. Walpole will collaborate with the Project Timber at OGI to link the Infopipe results to reactive programming with time constraints. Prof. Ahamad will work on the security aspects and distributed communications and Prof. Smaragdakis will work on programming language support. The research is divided into three parts.

Conceptual Research. The first part is the characterization and modeling of information flow in New Embedded Systems (NES) and applications, particularly regarding the differences between NES (connected and I/O-intensive) and classic embedded systems (self-contained and primarily computation-driven). The goal of this effort is on the definition of systemic QoS properties relevant to NES. The QoS properties will take priority in the implementation efforts.

Embedded Infopipe Toolkit. The second part is the development of the Infopipe toolkit for NES applications. The main difference between the Embedded Infopipe Toolkit and the generic Infopipe Toolkit is the support for systemic QoS properties specific to NES (e.g., predictable information delivery under constrained resources) and program properties (e.g., small memory footprint and low power consumption). These requirements will take priority in the Infopipe software development. Additional software tools will be developed to support these Infopipe software packages. The tools include the library of pre-fabricated Infopipes, program specializer, and Infopipe composer, all of which will support the NES requirements.

Evaluation and Demo Applications. The third part is the building of NES applications to demonstrate Infopipe software, and the evaluation of Infopipe software in the context of Open Experimental Platforms (OEPs). The current demo scenario is the adaptive bandwidth management for multiple UAVs transmitting large amounts of video data through a shared wireless network. The main contribution of our demo is the source-based filters implemented using ECho publish/subscribe facility. These filters are dynamically linked directly to ECho publisher at the video sources and therefore can save wireless network bandwidth by reducing video data before it reaches the network.

Management Plan. Prof. Pu (the PI) will work closely with the faculty members in this project, and hold regular meetings with the GRAs, the staff scientists (either a postdoc or a research programmer), and the consultants. The PI will be the focal point of the project, as well as the coordinator with the Infosphere participating faculty and partners. The PI will also lead the research in the area of specialization, assisted by the co-PIs. Prof. Liu will help the PI manage the project and students at Georgia Tech, and to transfer technology from previous DARPA-funded projects. Prof. Liu will lead the research in Infopipe data management under resource constraints. Prof. Schwan will lead the research in Infopipe adaptation and restructuring at the middleware layer. Prof.

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Walpole will lead the research in quality of service and collaborate with Project Timber at OGI. Prof. Ahamad will lead the research in security and distributed communications. Prof. Smaragdakis will lead the research in programming language support for module composition. The consultants (Prof. Charles Consel and Prof. Gregor Kiczales, among others) will work with the entire team in providing specific expertise.

4 Performance Against Plan

On the technical side, the project has moved forward with the planned personnel and sub-projects. On the whole, the project made good progress and produced good results, as explained in Section 5.

5 Major Accomplishments

5.1 Technical Accomplishments at Georgia Tech

5.1.1 00Q3

Project Coordination. We have planned and started research efforts that build on Infosphere results and apply them to Embedded Infopipe project. Several of the Infopipe software currently under development, including the XML level and the Middleware level implementations, are being retargeted towards embedded platforms such as PDAs. We have started two participating faculty (Ahamad and Smaragdakis) in the project. We also hired a programmer (James Adam Sigler) and a GRA (Galen Swint).

AOP. We have started the investigation of using Aspect-Oriented Programming in our software (Wei Han). This work is divided into two parts. First, we are using AspectJ compiler and AOP methodology in our software development. Specifically, AspectJ is being used in the development of XML level infopipe software. Second, we are using our experience to refine the AspectJ compiler. Currently, AspectJ provides minimal support for the correct serialization of code from interwoven aspects that depend on each other. There is no explicit support for specification of aspect-related code layout when dependencies exist. We have proposed a simple syntax for such specification and implementation strategy to generate correct code.

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program), especially Mark Jones and Johan Nordlander (the new postdoc). Nordlander has started a prototype implementation of Infopipes in his O'Haskell language. Basically, we are trying to understand the requirements for a real-time programming language that will enable the construction of Infopipe-like Information flow applications in embedded systems.

5.1.2 00Q4

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5.1.3   01Q1

Project Coordination. In addition to ongoing efforts to apply Infosphere results to Embedded Infopipes, we also have started several research efforts that are specifically targeted on the embedded applications. Some of the efforts will be outlined here.

Wireless Demo. The GT team (Schwan) started building a demo program to showcase the adaptation capabilities of PBIO and ECho software. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. The bandwidth consumption limitations are implemented by dynamic insertion of appropriate filters into the information flow (sources, in this case) to reduce the number of bits entering the system. Each filter is simple and controls one aspect of the information flow (resolution reduction, color reduction, etc). The composite system is very efficient because of the dynamic code generation and linking capabilities of ECho.

Java Program Recomposition. The GT team (Smaragdakis) has been developing a system for decomposing and recomposing Java programs at run-time. The purpose is to monitor the communications and control flow among the distributed Java components, so the program execution can be optimized by placing the program components in the most appropriate locations. The software tools for program monitoring, movement, and recomposition are being readied for an application on Infosphere software such as the Java version of Infopipes.

Time-Sensitive Consistency Model. The GT team (Ahamad) has been developing a time-sensitive consistency model that supports the delivery of information with time constraints. This is the continuation of work that was previously supported by NSF (and published as the best paper in the ICDCS'01, Phoenix). The current effort focuses on the experimental validation, refinement, and application of the software to information flow applications through Infopipe abstractions.

Aspect-Oriented Development of Infopipes. The GT team (Liu and Pu) has been re-developing the Java version of Infopipe software using AOP concepts and techniques. Specifically, the performance monitoring components (e.g., latency and bandwidth of network) of Infopipes have been coded as aspects and the AspectJ compiler has been used to generate the executable code. This is another example of raising the level of abstraction of the library code that supports ISG. (The other example is the threads package being developed at OGI.)

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program) on the modeling and verification of information flows in the context of reactive programming. The threads package outlined in the previous section, for example, supports a reactive programming model that can be integrated with Timber concepts and software.

5.1.4 01Q2

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Secure Information Flow Model. The GT team (Ahamad) has been developing a secure information flow model for Infosphere like systems has been developed. In this mandatory access control model, security labels are associated with information flows. The generation of such labels when information flows are manipulated (e.g., created, merged, filtered), label comparison and their usage as credentials for allowing access are being explored. In a distributed setting, key management akin to secure multicast has also been explored for ensuring confidentiality of information flows.

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Wireless Demo. The GT team started building a demo program to showcase the adaptation capabilities of PBIO and ECho software. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. The bandwidth consumption limitations are implemented by dynamic insertion of appropriate filters into the information flow (sources, in this case) to reduce the number of bits entering the system. Each filter is simple and controls one aspect of the information flow (resolution reduction, color reduction, etc). This work was started by Prof. Schwan and two of his graduate students (Bustamante and Widener). This demo is being refined and integrated with the BBN multi-UAV demo by Prof. Pu and the project programmer (Yan), with cooperation from Widener.

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- Yannis Smaragdakis. "Layered Programming with Unix Dynamic Libraries", to appear in the Proceedings of the 7th International Conference on Software Reuse (ICSR), April 2002.

Secure Information Flow Model. The GT team (Ahamad) has been developing a secure information flow model for Infosphere like systems has been developed. This effort has been redirected to other funding sources due to anticipated budget cuts in PCES.

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5.1.7 02Q1

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Java Program Recomposition. The GT team (Smaragdakis) has been developing a system for decomposing and recomposing Java programs at run-time. The purpose is to monitor the communications and control flow among the distributed Java components, so the program execution can be optimized by placing the program components in the most appropriate locations. Two papers have been accepted for publication.

- "FC++: Functional tools for object-oriented tasks," by Yannis Smaragdakis and Brian McNamara. Accepted for publication in Software Practice and Experience.
- "J-Orchestra: Automatic Java Application Partitioning", by Eli Tilevich and Yannis Smaragdakis. Accepted at the European Conference on OO Programming (ECOOP 2002).

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Quorum program) for integration with the BBN demo. This effort has been slowed down due to budget cuts in PCES.

5.1.8 02Q2

Infopipe Software Tools. We have been working on the continued development of Infopipe software, both at the middleware and at the application layers. The main accomplishment in this quarter is the completion of a technical report that summarizes our work on Infopipe software and tools. This paper was submitted to OSDI'02.

- Implementing Infopipes: The SIP/XIP Experiment, by Calton Pu, Galen Swint, Charles Consel, Younggyun Koh, Ling Liu, Koichi Moriyama, Jonathan Walpole, Wenchang Yan. Technical Report GT-CC-02-31, College of Computing, Georgia Institute of Technology, May 2002.

The technical report describes the work demonstrated at the April PCES PI Meeting, plus the experiments conducted on the Infopipe tools and code generated by the tools. One of the main technical innovations in the design and implementation of Infopipe software tools is the adoption of an XML-based intermediate language (XIP) to describe the meta-information in the information flow (instance metadata) as well as the Infopipe construction (type metadata).

Middleware Infopipes. We have been working on the development of Infopipe software based on PBIO at the Middleware Layer. The work in the Middleware Layer builds on the results from ECho and JECho software. The ECho middleware is one of the main components of the Embedded Infopipe software substrates. The Infopipe software integrated into the BBN OEP and demonstrated in the April PI Meeting is based on ECho middleware.

Information Flow Application Support. As part of the Infopipe development at the Application Layer, we also have been working on methods and software to extract information automatically from the Web. These are tools that facilitate the information flow by adding syntactic and semantic descriptions to Web-originated information flows such as dynamic web content. Prof. Liu is leading this effort. This effort is complementary to the Infopipe software tool development, particularly in the adoption of XML for representing metadata describing information flow. Two papers that have been accepted for publications are:

- Information Monitoring on the Web: A Scalable Solution, by L. Liu, W. Tang, D. Buttler, C. Pu, to appear in the journal *World Wide Web: Internet and Web Information Systems*, Kluwer Academic.
- A New Document Placement Scheme for Cooperative Web Caching, by Lakshmish Ramaswamy and Ling Liu, to appear in *Proceedings of the 22nd International Conference on. Distributed Computing Systems* (ICDCS 2002). July 2-5, 2002 - Vienna, Austria (IEEE Press).

Java Program Recomposition. The GT team (Smaragdakis) has been developing a system for decomposing and recomposing Java programs at run-time. The purpose is to monitor the communications and control flow among the distributed Java components, so the program execution can be optimized by placing the program components in the most appropriate locations. One paper has been accepted for publication and one has been presented in June 2002.

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- "FC++: Functional tools for object-oriented tasks," by Yannis Smaragdakis and Brian McNamara. Accepted for publication in Software Practice and Experience.
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Multi-UAV Demo. The GT team has successfully demonstrated the Embedded Infopipe using PBIO and ECho software as well as its integration with the BBN OEP at the April PI Meeting. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. This is informally known as the "Source-Based Filtering" capability in the BBN Multi-UAV demo. Further integration with the BBN OEP has been proposed.

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program) on the modeling and verification of information flows in the context of reactive programming. The threads package outlined in the previous section, for example, supports a reactive programming model that can be integrated with Timber concepts and software. In addition, the OGI team has been adapting a wireless video source mounted on a robot car (originally developed under the Quorum program) for integration with the BBN demo.

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Infopipe Software Tools. We have been working on the continued development of Infopipe software, both at the middleware and at the application layers. The main accomplishment in this quarter is the completion of a technical report that summarizes our work on Infopipe software and tools. This paper was revised and submitted to ICDCS'03.

- Implementing Infopipes: The SIP/XIP Experiment, by Calton Pu, Galen Swint, Charles Consel, Younggyun Koh, Ling Liu, Koichi Moriyama, Jonathan Walpole, Wenchang Yan. Technical Report GT-CC-02-31, College of Computing, Georgia Institute of Technology, May 2002.

The technical report describes the work demonstrated at the April PCES PI Meeting, plus the experiments conducted on the Infopipe tools and code generated by the tools.

There are several technical innovations in the design and implementation of Infopipe software tools. The first is the adoption of an XML-based intermediate language (XIP) to describe the meta-information in the information flow (instance metadata) as well as the Infopipe construction (type metadata). The second is the use of XIP to generate code for several underlying substrates, including ECho, the CORBA AV Stream, sockets, and Java RMI. The information filtering capability (e.g., reduction of frames or resolution, compression, and encryption) in response to resource constraint changes to maintain QoS requirements has increased at the same time. We plan to demonstrate some of these new capabilities in the December PI meeting.

Middleware Infopipes. We have continued the development of middleware Infopipe software beyond PBIO to include other middleware substrates such as CORBA (AV Streams) and Java (RMI). This work extends the results from ECho and JECho software. The ECho middleware is one of the main components of the Embedded Infopipe software substrates. We plan to incorporate this new middleware Infopipe software into the BBN OEP and Multi-UAV demo.

QoS Management. We have also started QoS management work supporting different quality aspects. One example is the support of security as a new QoS dimension. This is part of the new Infopipe capability mentioned above in the form of encryption filters added to the Infopipe composition. We also have some results at the kernel level, which are aimed at connecting wireless machines to cluster servers. This is expected to be useful for the Multi-UAV demo. Two papers accepted for publication are:

- Power-Aware Video Decoding using Real-Time Event Handlers, by Christial Poellabauer and Karsten Schwan, International Workshop on Wireless Mobile Multimedia, IEEE, Oct. 2002.

- Kernel Support for the Event-based Cooperation of Distributed Resource Managers, by Christian Poellabauer and Karsten Schwan, International Symposium on Real-time Systems and Applications (RTAS), ACM/IEEE, Oct. 2002.

Information Flow Application Support. As part of the Infopipe development at the Application Layer, we also have been working on methods and software to extract information automatically from the Web. These are tools that facilitate the information flow by adding syntactic and semantic descriptions to Web-originated information flows such as dynamic web content. Prof. Liu is leading this effort. This effort is complementary to the Infopipe software tool development, particularly in the adoption of XML for representing metadata describing information flow. One paper was presented:

- A New Document Placement Scheme for Cooperative Web Caching, by Lakshmish Ramaswamy and Ling Liu, to appear in *Proceedings of the 22nd International Conference on. Distributed Computing Systems* (ICDCS 2002). July 2-5, 2002 - Vienna, Austria (IEEE Press).

Papers that have been accepted for publications:

- Information Monitoring on the Web: A Scalable Solution, by L. Liu, W. Tang, D. Buttler, C. Pu. To appear in the journal *World Wide Web: Internet and Web Information Systems*, Kluwer Academic.

- Ginga: A Self-Adaptive Query Processing Service, by Henrique Paques, Ling Liu, Calton Pu. Short paper to appear in Proceedings of ACM International Conference on Information and Knowledge Management (CIKM), November 2002.
- Distributed Query Adaptation and Its Tradeoffs, by Henrique Paques, Ling Liu, Calton Pu. In the *Proceedings of the 18th Association of Computing Machinery Symposium on Applied Computing (CompSAC'03), Special Track on Database Technology.* March 2003, Melbourne, Florida.

Java Program Recomposition. The GT team (Smaragdakis) has been developing a system for decomposing and recomposing Java programs at run-time. The purpose is to monitor the communications and control flow among the distributed Java components, so the program execution can be optimized by placing the program components in the most appropriate locations. One paper has been accepted for publication:

- "FC++: Functional tools for object-oriented tasks," by Yannis Smaragdakis and Brian McNamara. Accepted for publication in Software Practice and Experience.

Secure Information Flow Model. The GT team (Ahamad) has been developing a secure information flow model for Infosphere like systems has been developed. This effort has been redirected to other funding sources due to anticipated budget cuts in PCES.

Aspect-Oriented Development of Infopipes. The GT team (Liu and Pu) has been re-developing the Java version of Infopipe software using AOP concepts and techniques. Specifically, the performance monitoring components (e.g., latency and bandwidth of network) of Infopipes have been coded as aspects and the AspectJ compiler has been used to generate the executable code. This is another example of raising the level of abstraction of the library code that supports ISG. This effort has been slowed down due to anticipated budget cuts in PCES.

Multi-UAV Demo. The GT team has successfully demonstrated the Embedded Infopipe using PBIO and ECho software as well as its integration with the BBN OEP at the April PI Meeting. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. This is informally known as the "Source-Based Filtering" capability in the BBN Multi-UAV demo. We have discussed some of the new Infopipe capabilities with BBN are planning the integration with the BBN OEP for either the December PI Meeting or the next PI meeting in Spring 2003.

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program) on the modeling and verification of information flows in the context of reactive programming. The threads package outlined in the previous section, for example, supports a reactive programming model that can be integrated with Timber concepts and software. In addition, the OGI team has been adapting a wireless video source mounted on a robot car (originally developed under the Quorum program) for integration with the BBN demo.

5.1.10 02Q4

Infopipe Software Tools. We have been working on the continued development of Infopipe software, both at the middleware and at the application layers. The main accomplishment in this quarter is the completion of a technical report that summarizes our work on Infopipe software and tools. This technical report is being revised for publication:

- Implementing Infopipes: The SIP/XIP Experiment, by Calton Pu, Galen Swint, Charles Consel, Younggyun Koh, Ling Liu, Koichi Moriyama, Jonathan Walpole, Wenchang Yan. Technical Report GT-CC-02-31, College of Computing, Georgia Institute of Technology, May 2002.

The technical report describes the work demonstrated at the April PCES PI Meeting, plus the experiments conducted on the Infopipe tools and code generated by the tools.

There are several technical innovations in the design and implementation of Infopipe software tools. The first is the adoption of an XML-based intermediate language (XIP) to describe the meta-information in the information flow (instance metadata) as well as the Infopipe construction (type metadata). The second is the use of XIP to generate code for several underlying substrates, including ECho, the CORBA AV Stream, sockets, and Java RMI. The information filtering capability (e.g., reduction of frames or resolution, compression, and encryption) in response to resource constraint changes to maintain QoS requirements has increased at the same time.

We are working on an "Infopipe Version of Multi-UAV Demo" for the next PI meeting. This demo will replace the currently hand-written application information flow with Infopipe software, generated by the Infopipe software tools. The demo will start with a high level specification in ISL (Infopipe Specification Language) of the entire Multi-UAV pipeline, from the video source (e.g., a video camera) to the destination (e.g., an X-window display). This ISL specification is translated into its corresponding XIP specification, including the data transport mechanisms and QoS requirements. The XIP specification is then translated into appropriate source code for several underlying platforms, which is then compiled into executable code. Currently we support two underlying platforms: CORBA AVStreams (primarily for interoperability with the current Multi-UAV demo application) and socket interface (the low overhead option).

Middleware Infopipes. We have continued the development of middleware Infopipe software beyond PBIO to include other middleware substrates such as CORBA (AV Streams) and Java (RMI). This work extends the results from ECho and JECho software. The ECho middleware is one of the main components of the Embedded Infopipe software substrates. In addition to AVStreams and sockets, ECho publish/subscribe and Java are two additional underlying platforms that we are planning to support for the ISL/XIP software toolkit.

QoS Management. We have also started QoS management work supporting different quality aspects. One example is the support of security as a new QoS dimension. This is part of the new Infopipe capability mentioned above in the form of encryption filters added to the Infopipe composition. We are incorporating these security filters into the Infopipe version of the Multi-UAV demo. Two papers published in 02Q4 are:

- Power-Aware Video Decoding using Real-Time Event Handlers, by Christial Poellabauer and Karsten Schwan, International Workshop on Wireless Mobile Multimedia, IEEE, Oct. 2002.
- Kernel Support for the Event-based Cooperation of Distributed Resource Managers, by Christian Poellabauer and Karsten Schwan, International Symposium on Real-time Systems and Applications (RTAS), ACM/IEEE, Oct. 2002.

Information Flow Application Support. As part of the Infopipe development at the Application Layer, we also have been working on methods and software to extract information automatically from the Web. These are tools that facilitate the information flow by adding syntactic and semantic descriptions to Web-originated information flows such as dynamic web content. Prof. Liu is leading this effort. This effort is complementary to the Infopipe software tool development, particularly in the adoption of XML for representing metadata describing information flow. Two papers were published in 02Q4 and a third was accepted for publication:

- Information Monitoring on the Web: A Scalable Solution, by L. Liu, W. Tang, D. Buttler, C. Pu. In the journal *World Wide Web: Internet and Web Information Systems*, (5)4: pp 263-304 (2002), Kluwer Academic.
- Ginga: A Self-Adaptive Query Processing Service, by Henrique Paques, Ling Liu, Calton Pu. Short paper to appear in Proceedings of ACM International Conference on Information and Knowledge Management (CIKM), November 2002.
- Distributed Query Adaptation and Its Tradeoffs, by Henrique Paques, Ling Liu, Calton Pu. In the *Proceedings of the 18th Association of Computing Machinery Symposium on Applied Computing (CompSAC'03), Special Track on Database Technology.* March 2003, Melbourne, Florida.

Java Program Recomposition. The GT team (Smaragdakis) has been developing a system for decomposing and recomposing Java programs at run-time. The purpose is to monitor the communications and control flow among the distributed Java components, so the program execution can be optimized by placing the program components in the most appropriate locations. One paper was published in 02Q4:

- "FC++: Functional tools for object-oriented tasks," by Yannis Smaragdakis and Brian McNamara, in Software Practice and Experience 32(10): 1015-1033 (2002).

Multi-UAV Demo. The GT team has successfully demonstrated the Embedded Infopipe using PBIO and ECho software as well as its integration with the BBN OEP at the April PI Meeting. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. This is informally known as the "Source-Based Filtering" capability in the BBN Multi-UAV demo. We are developing the next generation Infopipe software tools, which will demonstrated in the next PCES PI Meeting as the

Infopipe Version of the Multi-UAV demo. We are discussing with BBN OEP team the potential integration of this version of demo into the OEP mainline.

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program) on the modeling and verification of information flows in the context of reactive programming. The threads package outlined in the previous section, for example, supports a reactive programming model that can be integrated with Timber concepts and software. In addition, the OGI team has been adapting a wireless video source mounted on a robot car (originally developed under the Quorum program) for integration with the BBN demo.

5.1.11 03Q1

Infopipe Software Tools. We have been working on the continued development of Infopipe software, both at the middleware and at the application layers. The main accomplishment in this quarter is the completion of a technical report that summarizes our work on Infopipe software and tools. This technical report is being revised for publication:

- Implementing Infopipes: The ISL/XIP Experiment, by Calton Pu, Galen Swint, Charles Consel, Younggyun Koh, Ling Liu, Koichi Moriyama, Jonathan Walpole, Wenchang Yan. Technical Report GT-CC-02-31, College of Computing, Georgia Institute of Technology, current version under revision.

The technical report describes the work originally demonstrated at the April 2002 PCES PI Meeting, plus the experiments conducted on the Infopipe tools and code generated by the tools since that time.

There are several technical innovations in the design and implementation of Infopipe software tools. The first is the adoption of an XML-based intermediate language (XIP) to describe the meta-information in the information flow (instance metadata) as well as the Infopipe construction (type metadata). The second is the use of XIP to generate code for several underlying substrates, including ECho, the CORBA AV Stream, sockets, and Java RMI. The information filtering capability (e.g., reduction of frames or resolution, compression, and encryption) in response to resource constraint changes to maintain QoS requirements has increased at the same time.

New Demo. We are continuing the work on an "Infopipe Version of Multi-UAV Demo" for the next PI meeting in June 2003. This demo will replace the previously hand-written application information flow with Infopipe software, generated by the Infopipe software tools. The demo will start with a high level specification in ISL (Infopipe Specification Language) of the entire Multi-UAV pipeline, from the video source (e.g., a video camera) to the destination (e.g., an X-window display). This ISL specification is translated into its corresponding XIP specification, including the data transport mechanisms and QoS requirements. The XIP specification is then translated into appropriate source code for several underlying platforms, which is then compiled into executable code. Currently we support two underlying platforms: CORBA AVStreams (primarily for interoperability with the current Multi-UAV demo application) and socket interface (the low overhead option).

Middleware Infopipes. We have continued the development of middleware Infopipe software beyond PBIO to include other middleware substrates such as CORBA (AV Streams) and Java (RMI). This work extends the results from ECho and JECho software.

The ECho middleware is one of the main components of the Embedded Infopipe software substrates. In addition to AVStreams and sockets, the ECho publish/subscribe and Java RMI are two additional underlying platforms that we are planning to support for the ISL/XIP software toolkit.

QoS Management. We have also started QoS management work supporting different quality aspects. One example is the support of encryption for security as a new QoS dimension and compression for performance. This is part of the new Infopipe capability mentioned above in the form of encryption filters added to the Infopipe composition. We are incorporating these security filters into the Infopipe version of the Multi-UAV demo. Two papers accepted for publication are:

- Service Morphing: Integrated System- and Application-Level Service Adaptation in Autonomic Systems, by Christian Poellabauer, Karsten Schwan, Sandip Agarwala, Ada Gavrilovska, Greg Eisenhauer, Santosh Pande, Calton Pu, and Matthew Wolf, in Proceedings of the 5th Annual International Workshop on Active Middleware Services (AMS 2003), Seattle, Washington, June 2003.

- Resource-Aware Stream Management with the Customizable *dproc* Distributed Monitoring Mechanisms, by Sandip Agarwala, Christian Poellabauer, Jiantao Kong, Karsten Schwan, and Matthew Wolf, in Proceedings of the 12th IEEE International Symposium on High Performance Distributed Computing (HPDC-12), Seattle, Washington, June 2003.

Information Flow Application Support. As part of the Infopipe development at the Application Layer, we also have been working on methods and software to extract information automatically from the Web. These are tools that facilitate the information flow by adding syntactic and semantic descriptions to Web-originated information flows such as dynamic web content. Prof. Liu is leading this effort. This effort is complementary to the Infopipe software tool development, particularly in the adoption of XML for representing metadata describing information flow. One paper was published in 03Q1 and another was accepted for publication:

- Distributed Query Adaptation and Its Tradeoffs, by Henrique Paques, Ling Liu, Calton Pu. In the *Proceedings of the 18th Association of Computing Machinery Symposium on Applied Computing (CompSAC'03), Special Track on Database Technology.* March 2003, Melbourne, Florida.

- PeerCQ: A Decentralized and Self-Configuring Peer-to-Peer Information Monitoring System, by Bugra Gedik and Ling Liu. To appear in the Proceedings of the 23rd International Conference on Distributed Computing Systems (ICDCS'03), Providence, RI, May 2003. This paper is the winner of ICDCS'03 Best Paper Award. (This is the second time a paper supported by this contract winning the ICDCS Best Paper Award. The first time was a paper by Ahamad et al in ICDCS'01.)

Java Program Recomposition. The GT team (Smaragdakis) has been developing a system for decomposing and recomposing Java programs at run-time. The purpose is to monitor the communications and control flow among the distributed Java components, so the program execution can be optimized by placing the program components in the most appropriate locations. One paper was accepted for publication in 03Q2:

- NRMI: Natural and Efficient Middleware, by Eli Tilevich and Yannis Smaragdakis, to appear in the Proceedings of International Conference on Distributed Computing Systems (ICDCS'03), Providence, RI, May 2003.

Multi-UAV Demo. The GT team has successfully demonstrated the Embedded Infopipe using PBIO and ECho software as well as its integration with the BBN OEP at the April PI Meeting. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. This is informally known as the "Source-Based Filtering" capability in the BBN Multi-UAV demo. We are developing the next generation Infopipe software tools, which will demonstrated in the next PCES PI Meeting as the Infopipe Version of the Multi-UAV demo. We are discussing with BBN OEP team the potential integration of this version of demo into the OEP mainline.

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program) on the modeling and verification of information flows in the context of reactive programming. The threads package outlined in the previous section, for example, supports a reactive programming model that can be integrated with Timber concepts and software. In addition, the OGI team has been adapting a wireless video source mounted on a robot car (originally developed under the Quorum program) for integration with the BBN demo. Our modular development approach based on Infopipes match well with the expected merger of BBN and Boeing OEPs in the PCES II program.

5.1.12 03Q3

Infopipe Software Tools. The Infopipe software has more features in the application layer than ever before. The major contribution to the Infopipe project during this period is that the system built on the Infopipe technology now can have layers of information filtering in the pipeline. Three layers have been introduced in the Infopipe. Each layer includes multiple filters which can be applied to the information passed through. The application of the filters can be optional at both the producer and the consumer ends. These layers are the image-centric layer, the data compression layer, and the information encryption layer. The image-centric layer has several filters dedicated to the pixel manipulation. For example, the pixel size of the color image can be reduced to 1/3 of the original size. The jpeg filter can be used to reduce the image size to as little as 1/25 of the original size. The compression layer includes some generic compression filters which can be applied not only to the image data but also to the text or binary data. The encryption layer can be used in building the secured Infopipes systems.

When the information flow passes the pipeline, different filters can be applied to the data. This will guarantee the end-to-end QoS.

The systems built on top of the layers can also be dynamically configured at runtime. Runtime reconfiguration ability is one goal of the PCES project. One realization of the Infopipe reconfiguration system is built on ACE+TAO. That means the reconfiguration component is able to be used by other TDs.

The technical report GT-CC-02-31 has been expanded and divided into several papers and technical reports for publication. These new set of papers include:

- Code Generation for WSLAs using AXpect, by Galen Swint and Calton Pu. This work describes the use of AOP concepts in the code generation component of Embedded Infopipes toolkit and is being submitted to the 2004 AOSD conference.
- The ISL/ISG Toolkit for Information Flow Applications, by Galen Swint[1], Calton Pu[1], Charles Consel[2], Younggyun Koh[1], Ling Liu[1], Koichi Moriyama[3], Jonathan Walpole[4], Wenchang Yan[1]. This work describes the software architecture of ISG and is being submitted for publication in the 2004 GPCE conference.

One of our ongoing works, in collaboration with the consultant Consel, resulted in a publication in 03Q3. This paper describes a domain-specific language (Spidle) that can generate very efficient and trusted code for embedded devices. This is in addition to the support of general purpose programming languages such as C, C++, and Java.

- Spidle: A DSL Approach to Specifying Streaming Applications, by Laurent Reveillere, C. Consel, H. Hamdi, C. Pu, L. Singaravelu, and H. Yu. In the *Proceedings of ACM Symposium on Generative Programming and Component Engineering* (GPCE 2003), September 2003, Erfurt, Germany.

New Demo. We presented a newly built "Multi-UAV Demo" during the June 2003 PI meeting. The demo was built with layers of the Infopipe filters. Part of the demo was generated by the ISG code generator. The generated code includes the code that helps the setup of the data connection. The generated code also includes the Infopipe representation of the information flow. The ISG code generator translates the QoS concerns, which is described in the ISL (Infopipe Specification Language), into the working software. This addresses the QoS requirement in the Infopipe systems. It also makes the adaptation possible from one endpoint to another.

The live video source starts from the sender (e.g., a video camera) and ends at the receiver (e.g., an X-window display). A graphical front-end is provided for tuning the QoS requirements at runtime.

Middleware Infopipes. We have continued the development of middleware Infopipe software beyond PBIO to include other middleware substrates such as CORBA (TAO AVStreams). This work extends the results from ECho and JECho software. The ECho middleware is one of the main components of the Embedded Infopipe software substrates. In addition to AVStreams and sockets, the ECho publish/subscribe and Java RMI are two additional underlying platforms that we are planning to support for the ISL/XIP software toolkit.

QoS Management. The current Infopipe system supports more QoS aspects. One example is the support of the encryption for security as a new QoS dimension and the compression for performance. This is part of the new Infopipe capability mentioned above in the form of encryption filters added to the Infopipe composition. We are incorporating these security filters into the Infopipe version of the Multi-UAV demo.

Information Flow Application Support. As part of ongoing work on support information flow applications, we have also published two papers in 03Q3 and one was accepted in the journal:

- Renato Fileto, Claudia Bauzer Medeiros, Ling Liu, Calton Pu, and Eduardo Delgado Assad. "Using Domain Ontologies to Help Track Data Provenance", Proceedings of SBBD 2003. (Symposium of the Brazilian Databases Conference)
- Aameek Singh, Mudhakar Srivatsa, Ling Liu and Todd Miller. "Apoidea: A Decentralized Peer-to-Peer Architecture for Crawling the World Wide Web" In: Proccedings of the ACM SIGIR workshop on Distributed IR, Aug. 1, 2003. Lecture Notes of Computer Science (LNCS) series, Springer Verlag
- Renato Fileto, Ling Liu, Calton Pu, Claudia Bauzer Medeiros, Eduardo Delgado Assad. "POESIA: An Ontological Workflow Approach for Composing Web Services in Agriculture", Accepted by the International Journal of Very Large Database Systems, Special issue on Semantic Web, Guest Editors: Vijay Atluri, Anupam Joshi, Yelena Yesha.

5.1.13 03Q4

Infopipe Software Tools. We have the first official release of the Infopipe software. The Infopipes-0.1 package has been posted on the project's website: http://www.cc.gatech.edu/projects/infosphere/software/.

This release of the Infopipe software toolkit includes several parts. One part is the Infopipe Specification Language (ISL/XIP). Another part is the code generator, the Infopipe Stub Generator (ISG). The other part is the Infopipe version of the "Multi-UAV demo". The release also has the RPM format targeting RedHat 7.1. We also have tested the released software on RedHat 7.3 without any problems.

Here are the major highlights of the release. The ISL has richer syntax compared to the previous release. We maintained the approach of adopting an XML-based intermediate language (XIP) to describe the meta-information in the information flow as well as the Infopipe construction. The XIP language has been improved so that it can describe more complex data types (e.g., array). The type metadata (pipe) has more attributes than before. The construction part can generate code for different abstract machines (different APIs) such as C/sockets and CORBA/AVstreams. The code generator itself has also been improved. There are changes in the order of the internal parsing steps. There is some optimization in the performance. The release includes two versions of the "Multi-UAV demo", one is implemented in C (BSD socket) and the other is implemented in C++ (TAO AVStreams).

Three of the new papers are being revised for publication.
- Code Generation for WSLAs using AXpect, by Galen Swint and Calton Pu. This work describes the use of AOP concepts in the code generation component of Embedded Infopipes toolkit and is being submitted to ICWS 2004.
- The ISL/ISG Toolkit for Information Flow Applications, by Galen Swint[1], Calton Pu[1], Charles Consel[2], Younggyun Koh[1], Ling Liu[1], Koichi Moriyama[3], Jonathan Walpole[4], Wenchang Yan[1]. This work describes the software architecture of ISG and is being submitted to GPCE 2004.
- Infopipes: Concepts and ISG Implementation, by Galen Swint, Calton Pu, and Koichi Moriyama. This paper summarizes the Infopipe abstraction as implemented by ISG. This is in contrast to earlier work on the general Infopipe abstraction.

New Demo. The GT team has come up with the idea of further incorporating the Infopipe technology with the OEP. The idea is to use QuO programming API to implement the Infopipe component. Two team members went to BBN (Boston) to meet with the OEP team and discuss this collaboration. In this case, the Infopipe can add more features to the existing OEP. One example is that various kinds of Infopipe filters can be used in the OEP directly. But that requires repackaging of the Infopipe software so that it can communicate with the OEP coherently.

Middleware Infopipes. Infopipe can be realized in one of the middleware substrates such as CORBA (TAO AVStreams). This work extends the results from ECho and JECho software. The ECho middleware is one of the main components of the Embedded Infopipe software substrates. In addition to TAO AVStreams and sockets, the ECho publish/subscribe and Java RMI are two additional underlying platforms that we are planning to support for the ISL/XIP software toolkit.

QoS Management. We are focusing on the trade-offs among the various QoS dimensions, including performance and security. Specifically, we are conducting a set of experiments to evaluate the trade-offs between CPU availability and network bandwidth availability in the use of adaptive compression. These experiments were originally conducted at the middleware level using Infopipes and now are progressing towards kernel and network parameter setting sensitivity evaluation.

Information Flow Application Support. Five papers were published in this area in support of information flow applications.

- Lakshmish Ramaswamy, Arun Iyengar, Ling Liu, Fred Douglis. "Automatic Detection of Fragments in Websites." In Proceedings of ACM International Conference on Information and Knowledge Management, November 2003.

- Keke Chen and Ling Liu, "Validating and Refining Clusters via Visual Rendering." In Proceedings of the IEEE Conference on Data Mining, 2003 (IEEE ICDM 2003). Melbourne, Florida, USA, November 19 - 22, 2003

- Bugra Gedik and Ling Liu. "Building Reliable Peer-to-Peer Information Monitoring Service Through Replication." In Proceedings of the 22nd Symposium on Reliable Distributed Computing (SRDS2003), 6th-8th/October, 2003 - Florence, Italy.

- Lakshmish Ramaswamy, Bugra Gedik, Ling Liu. "Connectivity Based Node Clustering in Decentralized Peer to Peer Networks". In Proceedings of the third IEEE Conference on Peer-to-Peer Computing, September 1-, Linkoping, Sweden.

- Aameek Singh and Ling Liu. "TrustMe: Anonymous Management of Trust Relationships in Decentralized P2P networks". In Proceedings of the third IEEE Conference on Peer-to-Peer Computing, September 1-, Linkoping, Sweden.

5.1.14 04Q1

Infopipe Software Tools. The team has worked on creating a graphical front-end for the Infopipe software tools. After extensive study in the field, we finally adopted Berkeley's Ptolemy tool as the front-end for the Infopipe language. The GUI front-end can help rapid development using Infopipe software.

Ptolemy tool has an internal representation of the system that is designed (graphically drag-and-drop) on the canvas. The Infopipe metadata can be perfectly described by the

actor library of the Ptolemy tool. The instances of the Infopipe can be arranged in Ptolemy and finally be used to build the system consisting of different Infopipe components. That means the Infopipe language (ISL/XIP) and thus the Infopipe system actually have a representation in the Ptolemy language. Taking the internal XML representation of the Infopipe system (in Ptolemy), we can find the exact mapping of the system described in the Infopipe language (XIP). Then the XIP is used to generate the code for the building blocks.

The GT team completed the work in realizing the Infopipe abstraction with the ECho middleware. ECho is a publish/subscribe event middleware system. It is different from the client/server model. If we can translate the Infopipe language into a system built on ECho, we are able to use the "source-based filtering" mechanism for the Infopipe QoS management. Several demonstrations of the Infopipe system (ECho version) have been developed to show how this works.

One of the new papers has been accepted for publication:
- Infopipes: Concepts and ISG Implementation, by Galen Swint, Calton Pu, and Koichi Moriyama. This paper summarizes the Infopipe abstraction as implemented by ISG. This is in contrast to earlier work on the general Infopipe abstraction. To appear in *Proceedings of the 2004 IEEE Workshop on Software Technologies for Future Embedded and Ubiquitous Computing Systems* (WSTFEUS 2004), Vienna, May 2004.

Two of the new papers have been submitted for publication:
- Code Generation for WSLAs using AXpect, by Galen Swint and Calton Pu. This work describes the use of AOP concepts in the code generation component of Embedded Infopipes toolkit. Submitted to the ICWS 2004.
- The ISL/ISG Toolkit for Information Flow Applications, by Galen Swint[1], Calton Pu[1], Charles Consel[2], Younggyun Koh[1], Ling Liu[1], Koichi Moriyama[3], Jonathan Walpole[4], Wenchang Yan[1]. This work describes the software architecture of ISG, submitted to GPCE 2004.

New Demo. The new demo is part of our efforts in integrating Infopipe technology into the OEP. The new UAV sender (video producer) now inherits most of the properties from both the BBN OEP sender and the Infopipe SenderPipe. The same approach applies to the UAV receiver (video consumer). The new UAV receiver now inherits most of the properties from both the BBN OEP receiver and the Infopipe ReceiverPipe. The information flow starts from the sender. The new demo uses the existing OEP functionality to capture the image (PPM). The image stream then passes through the Infopipe pipeline (various filters) before it's sent out to the wire. On the consumer side, the image stream goes through the Infopipe pipeline first before it can be grabbed by the ATR (automatic target recognition). In addition to all the existing QoS management schemes in OEP, Infopipe filters provides more adaptation mechanisms to the UAV system. The demo was presented at the December 2003 PI meeting.

Middleware Infopipes. Infopipe can not only generate code in one of the middleware substrates such as CORBA (TAO AVStreams), but also it can be plugged into certain middleware system (OEP) as well. In addition to TAO AVStreams and sockets, the ECho publish/subscribe and Java RMI are two additional underlying platforms that we are planning to support for the ISL/XIP software toolkit.

QoS Management. Starting from the 4th quarter in 2003, the PCES project has a guideline for the experiments conducted by all the participants. The guideline is called Goal-Question-and-Metrics (GQM). The Emulab becomes the testbed for most of the TDs to complete their experimentations for their technologies. The GT team has designed and conducted a series of experiments to evaluate the Infopipe technology within the OEP context. By targeting the PCES goals of end-to-end and roundtrip QoS (GQ1) and rapid reaction and reconfiguration (GR1), we propose one new question, and hence one new experiment with four new metrics. One configuration is based on the so-called Baseline configuration. The other configuration has the Infopipe filters inserted into so that it can be used to compare with the Baseline configuration.

The following metrics were collected: Average rate (fps) of the important video frames arriving at the receiver; Average latency (one way) of the important video arriving at the receiver; Standard deviation of the latency of the important video arriving at the receiver; Maximum latency of the important video arriving at the receiver.

The experiments were conducted in Emulab. The result showed that the Infopipe technology can improve the delivery of the UAV under (increasing) network load.

Adaptive Compression. There is one research effort that is being completed as it may still be useful for the OEP. The Fine-Grain (FG) Mixing strategy compresses and sends as much data as possible, and then uses any remaining bandwidth to send uncompressed packets. The main problem is with non-trivial interactions between system components and layers (e.g., compression programs and OS/network parameter settings such as block size and buffer size) that result in significant impact on the overall system performance. We are working on the following paper:

- Fine-Grain Adaptive Compression in Dynamically Variable Networks, by Calton Pu and Lenin Singaravelu.

5.1.15 04Q2

Infopipe Software Tools. A new release of the Infopipe Software Toolkit (Release 0.9) has been published in the public domain. The toolkit can be downloaded from the project's website:

http://www.cc.gatech.edu/projects/infosphere/software.

This release of the Infopipe toolkit contains the source code and libraries required to build ISG -- the Infopipe Stub Generator. The goal of the ISG and the Infopipe project is to create a high level abstraction in communication channels of the information flow. Dynamic adaption, QoS management and aspects are also the research topics of the Infopipe project.

There're several major changes from the 0.1 release.

- Major changes in the code generator, the ISG. The new ISG can produce code for different aspects in the distributed system.
- Most of the XSLT templates provided have been updated. The ISG can generate code in different languages like C, C++ and Java. It also can generate code for BSD socket API, TAO AVStreams, and the ECho event middleware.
- The UAV2 demonstration has been updated.

- Autoconf and automake packages never come with the installation anymore.

Two of the Infopipe papers have been presented in conferences or workshops:

- Infopipes: Concepts and ISG Implementation, by Galen Swint, Calton Pu, and Koichi Moriyama. This paper summarizes the Infopipe abstraction as implemented by ISG. This is in contrast to earlier work on the general Infopipe abstraction. Presented and published in *Proceedings of the2004 IEEE Workshop on Software Technologies for Future Embedded and Ubiquitous Computing Systems* (WSTFEUS 2004), Vienna, May 2004.
- Code Generation for WSLAs using AXpect, by Galen Swint and Calton Pu. This work describes the use of AOP concepts in the code generation component of Embedded Infopipes toolkit. Presented and published in the *Proceedings of the 2004 IEEE International Conference on Web Services* (ICWS 2004), San Diego, July 2004. This paper was awarded the Best Student Paper of the Conference.

Another of the Infopipe papers has been accepted for publication:

- The ISL/ISG Toolkit for Information Flow Applications, by Galen Swint[1], Calton Pu[1], Charles Consel[2], Younggyun Koh[1], Ling Liu[1], Koichi Moriyama[3], Jonathan Walpole[4], Wenchang Yan[1]. This work describes the software architecture of ISG, submitted and accepted by the *2004 IEEE Symposium on Network Computing and Applications* (NCA'04), Boston, August 2004.

In addition, several "infrastructure and techniques" papers have been published or accepted for publication. These are papers describing techniques that are useful for information flow applications or future Infopipe technology. Two of the papers are directly related to the Infopipe work in the area of system software specialization:

- Remote Customization of Systems Code for Embedded Devices, by Sapan Bhatia, Charles Consel, and Calton Pu. In *Proceedings of the Fourth ACM International Conference on Embedded Software* (EMSOFT 2004), Pisa, Italy, September 2004.
- Efficient Mediators through Dynamic Code Generation: a Method and an Experiment, by Yasushi Shinjo, Toshiyuki Kubo and Calton Pu. To appear in a special issue of *Information and Software Technology* on ACM SAC'03 conference papers.

Five of the papers are in the area of communications support for information applications that can be used in future Infopipe software toolkits:

- Ling Liu, Wei Tang, David Buttler, and Calton Pu. Information Monitoring on the Web: A Scalable Solution. World Wide Web Journal (by Kluwer Academic Publishers), Volume 5, No. 4.
- Bugra Gedik and Ling Liu. "MobiEyes: Distributed Processing of Continuously Moving Quer ies on Moving Objects in a Mobile System", Proceedings of the 9th International Conference on Extending Database Technology (EDBT), March 14-18, 2004 (Heraklion - Crete).
- BizCQ: Using Continual Queries to Cope with Changes in Business Information Exchange, by Wei Tang, Kipp Jones, Ling Liu, Calton Pu. In *Proceedings of the 10th International Conference on World Wide Web*, May 17-22, 2004. New York, Poster Paper, pp 470-471.
- Reliable Peer-to-peer End System Multicasting through Replication, by Jianjun Zhang, Ling Liu, Calton Pu, and Mostafa Ammar. In *Proceedings of the Fourth*

IEEE Conference on Peer-to-Peer Computing (P2P 2004), Zurich, Switzerland, August 2004.

- A Dynamic Two-Phase Commit Protocol for Self-Adapting Services, by Weihai Yu, Yan Wang, and Calton Pu. In *Proceedings of the 2004 IEEE Service Computing Conference* (SCC 2004), Shanghai, China, September 2004.

Three of the papers are in the area of information management support for information flow applications that can be incorporated into Infopipe libraries in the future:

- James Caverlee, Ling Liu, and David Buttler. "Probe, Cluster, and Discover: Focused Extraction of QA-Pagelets from the Deep Web", Proceedings of the 20th IEEE International Conference on Data Engineering (ICDE 2004), March 30-April 2, 2004 (Boston, USA).

- Efficient Web Change Monitoring with Page Digest, by David Buttler, Dan Rocco, Ling Liu. In *Proceedings of the 10th International Conference on World Wide Web*, May 17-22, 2004. New York, Poster Paper, pp 476-477.

- Automatic Detection of Fragments in Dynamically Generated Web Pages, by Lakshmish Ramaswamy, Arun Iyengar, Ling Liu, Fred Douglis. In *Proceedings of the 10th International Conference on World Wide Web*, May 17-22, 2004. New York, pp 443-453. This paper received the Best Paper award for the conference.

Middleware Infopipes. The latest Infopipe software can create distributed systems for two kinds of middleware substrates, CORBA (TAO AVStreams) and ECho. The ECho middleware is one of the main components of the Embedded Infopipe software substrates. In addition to AVStreams and ECho publish/subscribe, Java RMI is the additional underlying platform that we are planning to support for the ISL/XIP software toolkit.

QoS Management. The GT team proposed one utility function of the QoS management for the multi-UAV system. This finally leads to new experimentation and transition. The application level QoS management scheme is called the Optimized Compression Rate (OCR) mechanism. It's a network usage based adaptation mechanism designed specifically for the PPM format image stream.

OCR management can be implemented in the form of QuO qosket(s). It can be used in the latest OEP. It addresses the concerns of the quality of the PPM image stream between the constrained network links.

The distributed system could have the resource contention in the CPU usage, the memory, and the connection link. While there're lots of approaches dealing with the network resource constraints, one of the key concerns is the amount of the bits passing along the communication link. If the system transmits the multimedia information, encoding is one of the effective ways to address the problem by compressing the data before they are sent out to the connection link. More specifically, some of the image compression algorithms are pretty good at compressing the image with or without loss of much information. Sometimes, the consumer side also requires continuous video feeds so that it can keep on track of any real-time mission critical task. That can mean that the video frame rate should be guaranteed even with the sacrifice of the quality of the image.

The OEP works under the assumption of the combat field scenario. One of the kinds of video formats OEP uses is the raw PPM image format. The link-16 has a bandwidth limit

of 115kbs. In addition, the changing environment of the battle field may require any kind of adaptation schemes to be able to be dynamically configurable at runtime.

We propose a QoS adaptation mechanism based on the network resource usage and the real-time quality of the PPM image stream. OCR can give the system advice on how much the data should be compressed assuming the availability of the image encoding algorithms and the negotiation between the quality of the video stream and the lossy compression. The advice can be adopted by the system depends on its capability on the manipulation of the image content.

OEP has several application level QoS management schemes. Some of them are based on Mpeg video streams and some of them are based on PPM format video streams. We want to contribute a general QoS mechanism so that an optimized compression ratio of the source PPM frame can adapt to the network constraints, yet the real-time requirement of the stream can still be guaranteed (in the sense of the frame rate requirement). The goal is to make this approach generic (in the form of qoskets) so that it can be used by other TDs. This QoS mechanism is based on the available bandwidth, the required fps, and other measurements such as the current fps and the current image compression ratio.

The data amount of the PPM image and the frame rate (or more exactly the network bandwidth) we have can be enforced upon by the following rule,

$$\frac{target\_compression\_ratio}{current\_compression\_ratio} = \frac{current\_frame\_rate}{target\_frame\_rate.}$$

The *target_compression_ratio* has the value between 0 and 1, with value 1 meaning no compression at all. Intuitively, if the network link has constraints, the observed *current_frame_rate* will drop, then the value of the *target_compress_ratio* should adjust itself down so that more compression is achieved. While there's more available bandwidth, the frame rate will go up and the loss rate of the image can drop and the value of the *target_compression_ratio* will go up. The reason we don't explicitly use bandwidth in the rule is because that the image stream doesn't necessarily consume much of the available bandwidth when the image scales down. There might be other approach of introducing an extra module to monitor the available bandwidth, but then it may result in extra competition on the already constrained communication link. The mechanism also works if the user wants to adjust the *target_frame_rate* at runtime.

5.2   Technical Accomplishments at OGI

5.2.1 00Q3

Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes. One of our GRAs, Ashvin Goel has made significant progress defining a "QoS-adaptive real-rate network service" which will form the basis of real-rate infopipes. He completed his thesis proposal document and proposal defense talk. We have made some good progress on defining packet formats for real-rate flows, understanding how traffic specifications should work, and more importantly,

understanding how to parameterize feedback control mechanisms and provision buffers so that real-rate scheduling can work along a pipeline.

Another one of our GRAs, Kang Li has been developing a feedback-based model of TCP-friendly congestion control -- basically, using feedback control ideas to understand the fine-grain dynamic behavior of TCP-like congestion control so that we can produce other real-rate transmission protocols that are truly TCP-friendly. He is working on his thesis proposal and has had several papers, including a poster he presented at SIGCOMM'2000. His accomplishments include:

- "Modeling the effect of short-term rate variations on TCP-friendly congestion control behavior" by Kang Li, Molly H. Shor, Jonathan Walpole, Calton Pu and David C. Steere, submitted to American Control Conference 2001.

- "Modeling the effect of a rate smoother on TCP-Friendly Congestion Control Behavior" by Kang Li, Jonathan Walpole, David Steere and Molly Shor. Work-in-progress poster in ACM SIGCOMM'2000, Stockholm Sweden.

In addition to the theoretical modeling work, he has produced some interesting MATLAB-based simulations for the bandwidth sharing among TCP flows. These can be used to demonstrate the dynamic behavior of bandwidth sharing under various packet loss models. The simulations are available on the web: http://www.cse.ogi.edu/~kangli/. Finally, he has modified the Linux kernel to let users adjust any TCP flow's AIMD increment and decrement parameters, allowing them to produce TCP flows with various levels of aggressiveness.

In the Application Layer, we have also done a lot of work to integrate the Quasar adaptive video pipeline and real-rate scheduling, so that they could be presented as part of the HiPer-D Demo 2000 event (part of the Quorum program). They were included in the first round demo and were considered a great success. This work can be seen a technology transition from Quasar into Infosphere and out into the Navy. It is a first level, primitive, prototype of our adaptive real-rate infopipe technology.

In addition, we have also been working on integrating our Infopipe work into Intel's new IXP1200 router platform, and also onto the Compaq iPAQ handheld computers. Both platforms have a StrongARM processor and we have a port of Linux running in each case. We are still integrating our software into this environment, so this is still work in progress.

5.2.2 00Q4

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes. In addition to a recently completed PhD thesis proposal by Ashvin Goel on real-rate network service for QoS-adaptive information flows, we also participated in the Quorum technology demonstrations at Naval Surface War Center (HiPer-D). The demonstration consists of the Quasar real-rate QoS-adaptive video pipeline and resource management components. We also demonstrated rudimentary real-rate Infopipes at the DARPA Ubiquitous Computing program PI meeting in Pittsburgh. The main publications in this area are:

- "Control and modeling issues in computer operating systems: resource management for real-rate computer applications," David Steere, Molly H. Shor, Ashvin Goel,

Calton Pu and Jonathan Walpole, Proceedings of the 39th IEEE Conference on Decision and Control, Sydney, Australia, December 12-15, 2000.

- "Progress-based resource management using feedback control," David Steere, Molly H. Shor, Ashvin Goel, Joshua Gruenberg, Dylan McNamee, Calton Pu, Jonathan Walpole, Real Time Systems, Special Issue on Control-Theoretical Approaches to Real-Time Computing, submitted for review and possible publication in January 2001.

Control-Based Adaptive Infopipes. We have been working on modeling, analysis, and design of computer operating system components to meet dynamic specifications, such as matching real rates required by infoflow applications in order to provide desired QoS. We have also modeled, analysed and designed network protocols and bandwidth schedulers. In addition to meeting dynamic rate and QoS specifications, we have explored their interactions with other network protocols and considered problems of interaction among several adaptive applications, system components, and protocols. The goal of this work is to help us understand what it will take to construct TCP-friendly Infopipes.

Shor, Walpole and Steere studied a "progress-based" resource allocation strategy for CPU scheduling and modeled it using a control-system-based modeling approach. They published and presented a simplified dynamic system model, comparison of model simulations with experimental data, and discussion of model strengths and shortcomings.

Shor, Walpole and Li, studied the dynamic behavior of TCP and other transport protocols, with an emphasis on "TCP friendliness". They used dynamic models to understand the interaction of different transport protocols in a network, the impact of packet error rate variations, packet smoothing, and greedy and non-greedy application behavior on "fair share" of network resources and on QoS guarantees. They also studied interactions between adaptive protocols (such as TCP) and adaptive applications (such as self-regulating adaptive QoS multimedia streams) to understand the overall dynamic behavior of interacting adaptive components in an information flow system.

Main publications in this area are:

- "Control Challenges in Multi-Level Adaptive Video Streaming," Dylan McNamee, Charles Krasic, Kang Li, Ashvin Goel, David Steere, and Jonathan Walpole, Proceedings of the 39th IEEE Conference on Decision and Control, Harbour, Australia, December 12-15, 2000.

- "Using feedback control for a network and CPU resource management application," Ashvin Goel, Molly Shor, Jonathan Walpole, David Steere, and Calton Pu, 2001 American Control Conference, submitted for review and possible publication in Sept. 2000.

- "Modeling the effect of short-term rate variations on TCP-friendly congestion control behavior," Kang Li, Molly H. Shor, Jonathan Walpole, Calton Pu and David C. Steere, 2001 American Control Conference, Alexandria, Virginia, submitted for review and possible publication in Sept. 2000.

We have also published (on the web http://www.cse.ogi.edu/~kangli/) some interesting MATLAB-based simulations for the bandwidth sharing among TCP flows. These can be

used to demonstrate the dynamic behavior of bandwidth sharing under various packet loss models.

Infopipe Abstractions. We continued to develop and refine the Infopipe abstractions. We completed an Infopipe prototype, in Smalltalk, with "polarity-checking" and polymorphic components. "Polarity checking" means that when pipes are connected, the connection is checked to ensure that active outputs are connected only to passive inputs, and that passive outputs are connected only to active inputs. A polymorphic component is one that can operate with either active or passive polarity. However, once the first connection is made, the polarity of the other end of the pipe is determined, and must pass the polarity check. These polarity checks ensure that it is possible for information to flow through the pipe, and hence constitute one of many correctness checks we would like to be able to do during Infopipe construction.

The prototype is currently limited to infopipes within a single machine. In the future we plan to extend this prototype to include network infopipes. We also plan to implement a monitoring interface that can be used to determine, for example, latencies and flow rates in particular components. Finally, we plan to test these extensions on some example applications, involving real-time audio or video.

Specialization TOCS Paper. Another publication that was accepted for publication in 00Q4 is a paper on our past work on system software specialization, which is a fundamental building block technology of the Infopipe research. This work was primarily funded by the Quorum program.

- Specialization Tools and Techniques for Systematic Optimization of System Software, by Dylan McNamee, Jonathan Walpole, Calton Pu, Crispin Cowan, Charles Krasic, Ashvin Goel, and Perry Wagle of OGI, and Charles Consel, Gilles Muller, and Renaud Marlet of IRISA, *ACM Transactions on Computer Systems*. To appear in the May 2001 issue.

Technology Transfer. In the Application Layer, we have completed our participation in the HiPer-D Demo 2000 event (part of the Quorum program). They were included in the first round demo and were considered a great success. It is a first level, primitive, prototype of our adaptive real-rate infopipe technology. In addition, we have also been working on integrating our Infopipe work into Intel's new IXP1200 router platform, and also onto the Compaq iPAQ handheld computers. Both platforms have a StrongARM processor and we have a port of Linux running in each case. We are still integrating our software into this environment, so this is still work in progress.

5.2.3 01Q1

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts. We completed an Infopipe prototype, in Smalltalk, with "polarity-checking" and polymorphic components. We are extending this prototype to include network infopipes and a monitoring interface that can be used to determine, for example, latencies and flow rates in particular components.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building

an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload. The main publications in this area are:

- "Progress-based resource management using feedback control," David Steere, Molly H. Shor, Ashvin Goel, Joshua Gruenberg, Dylan McNamee, Calton Pu, Jonathan Walpole, Real Time Systems, Special Issue on Control-Theoretical Approaches to Real-Time Computing, submitted for review and possible publication in 2001.

Threads Support in Infopipes. We have been developing a middleware package that supports the Infopipe abstractions and interface, but hides some of the complexity in managing threads, including concurrency, synchronization, and scheduling. This package makes the "computational" aspects of an Infopipe implementation more transparent to the kernel and middleware programmer of Infopipes. This package will be useful as a higher level library that supports more directly the code generated by the ISL Stub Generator.

Specialization TOCS Paper. A significant journal paper to be published in early 2001 is a paper on our work on system software specialization, which is a fundamental building block technology of the Infopipe research. This work was primarily funded by the Quorum program.

- Specialization Tools and Techniques for Systematic Optimization of System Software, by Dylan McNamee, Jonathan Walpole, Calton Pu, Crispin Cowan, Charles Krasic, Ashvin Goel, and Perry Wagle of OGI, and Charles Consel, Gilles Muller, and Renaud Marlet of IRISA, *ACM Transactions on Computer Systems*. To appear in the May 2001 issue.

Technology Transfer. In the Kernel and Application Layers, we have completed our participation in the HiPer-D Demo 2000 event (part of the Quorum program). They were included in the first round demo and were considered a great success. It is a first level, primitive, prototype of our adaptive real-rate infopipe technology. In addition, we have also been working on integrating our Infopipe work into Intel's new IXP1200 router platform, and also onto the Compaq iPAQ handheld computers. Both platforms have a StrongARM processor and we have a port of Linux running in each case. This is still work in progress, with increasing other funding sources such as Intel.

5.2.4 01Q2

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts. We completed an Infopipe prototype, in Smalltalk, with "polarity-checking" and polymorphic components. We are extending this prototype to include network infopipes and a monitoring interface that can be used to determine, for example, latencies and flow rates in particular components.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building

an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload. The main publications in this area are:

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Specialization TOCS Paper. A significant journal paper to be published in early 2001 is a paper on our work on system software specialization, which is a fundamental building block technology of the Infopipe research. This work was primarily funded by the Quorum program.

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Technology Transfer. In the Kernel and Application Layers, we have completed our participation in the HiPer-D Demo 2000 event (part of the Quorum program). They were included in the first round demo and were considered a great success. It is a first level, primitive, prototype of our adaptive real-rate infopipe technology. In addition, we have also been working on integrating our Infopipe work into Intel's new IXP1200 router platform, and also onto the Compaq iPAQ handheld computers. Both platforms have a StrongARM processor and we have a port of Linux running in each case. This is still work in progress, with increasing other funding sources such as Intel.

5.2.5 01Q3

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts. We completed an Infopipe prototype, in Smalltalk, with "polarity-checking" and polymorphic components. We are extending this prototype to include network infopipes and a monitoring interface that can be used to determine, for example, latencies and flow rates in particular components.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building

an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload. The following papers were presented and appeared in published proceedings:

- "The Minimal Buffering Requirements of Congestion Controlled Interactive Multimedia Applications," Kang Li, Charles Krasic, Jonathan Walpole, Molly Shor, and Calton Pu, In Proceedings of the 8th International Workshop on Interactive Distributed Multimedia Systems -- iDMS 2001, Lancaster, UK, September 2001. Also published in Springer Verlag`s Lecture Notes in Computer Science Series LNCS volume 2158, pages 181-192.

- "The Case for Streaming Multimedia with TCP," Buck Krasic, Kang Li and Jonathan Walpole, In proceedings of the 8th International Workshop on Interactive Distributed Multimedia Systems -- iDMS 2001, Lancaster, UK, September 2001. Also published in Springer Verlag`s Lecture Notes in Computer Science Series LNCS volume 2158, pages 213-218.

The following papers were accepted for publication during Q3 2001, and have since been presented, but the presentation occurred in Q4 2001.

- "Reifying Communication at the Application Level," Andrew Black, Jie Huang and Jonathan Walpole, In Proceedings of the International Workshop on Multimedia Middleware, Ottawa, Canada, October 2001. Also availabile as OGI Technical Report CSE-01-006, June 2001.

- "Priority-Progress Streaming for Quality-Adaptive Multimedia," Buck Krasic and Jonathan Walpole, In Proceedings of the ACM Multimedia Doctoral Symposium, Ottawa, Canada, October 2001.

- "Infopipes for Composing Distributed Information Flows," Rainer Koster, Andrew Black, Jie Huang, Jonathan Walpole and Calton Pu, In Proceedings of the ACM Multimedia Workshop on Multimedia Middleware, Ottawa, Canada, October 2001. Also appears as OGI Technical Report CSE-01-005.

- "Thread Transparency in Information Flow Middleware," Rainer Koster, Andrew Black, Jie Huang, Jonathan Walpole and Calton Pu, in Proceedings Middleware 2001 - IFIP/ACM International Conference on Distributed Systems Platforms, Heidelberg, Germany, November 12-16, 2001. Also appears as OGI Technical Report CSE-01-004.

Papers submitted for publication and pending:

- "Progress-based resource management using feedback control," David Steere, Molly H. Shor, Ashvin Goel, Joshua Gruenberg, Dylan McNamee, Calton Pu, Jonathan Walpole, Real Time Systems, Special Issue on Control-Theoretical Approaches to Real-Time Computing, submitted for review and possible publication in 2001.

Threads Support in Infopipes. We have been developing a middleware package that supports the Infopipe abstractions and interface, but hides some of the complexity in managing threads, including concurrency, synchronization, and scheduling. This

package makes the "computational" aspects of an Infopipe implementation more transparent to the kernel and middleware programmer of Infopipes. This package will be useful as a higher level library that supports more directly the code generated by the ISL Stub Generator.

5.2.6   01Q4

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts. A paper was submitted for publication.

- Infopipes: an Abstraction for Multimedia Streaming, by Andrew P. Black, Jie Huang, Rainer Koster, Jonathan Walpole,Calton Pu, submitted to Springer-Verlag Multimedia Systems Journal.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload. The following papers were presented and appeared in published proceedings:

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Papers accepted for publication:

- "Gscope: A Software Oscilloscope for Vizualizing Time-Sensitive Applications," Ashvin Goel and Jonathan Walpole, to appear in proceedings of the Freenix Track of the 2002 USENIX Annual Technical Conference, Monterey, California, June 2002.

5.2.7 02Q1

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload.

Papers accepted for publication:

- "Gscope: A Software Oscilloscope for Vizualizing Time-Sensitive Applications," Ashvin Goel and Jonathan Walpole, to appear in proceedings of the Freenix Track of the 2002 USENIX Annual Technical Conference, Monterey, California, June 2002.

- "Infopipes: An Abstraction for Multimedia Streaming," Andrew Black, Rainer Koster, Jie Huang, Jonathan Walpole, and Calton Pu, to appear in ACM / Springer Verlag Multimedia Systems Journal.

- "Supporting Low-Latency TCP-Based Media Streams," Ashvin Goel, Buck Krasic, Kang Li, Jonathan Walpole, to appear in the International Workshop on Quality of Service (IWQoS) 2002.

Papers submitted:

"A Measurement-Based Analysis of the Real-Time Performance of the Linux Kernel," Luca Abeni, Ashvin Goel, Buck Krasic, Jim Snow, and Jonathan Walpole, in submission to the Real Time Technology and Applications Symposium (RTAS 2002), submitted March 2002.

5.2.8 02Q2

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts. A paper has been accepted for publication:

- Infopipes: An Abstraction for Multimedia Streaming, by Andrew Black, Rainer Koster, Jie Huang, Jonathan Walpole, and Calton Pu, to appear in *Multimedia Systems Journal*, ACM Press and Springer Verlag.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload.

Papers presented in this Quarter:

- "Gscope: A Software Oscilloscope for Vizualizing Time-Sensitive Applications," Ashvin Goel and Jonathan Walpole, to appear in proceedings of the Freenix Track of the 2002 USENIX Annual Technical Conference, Monterey, California, June 2002.
- "Supporting Low-Latency TCP-Based Media Streams," Ashvin Goel, Buck Krasic, Kang Li, Jonathan Walpole, to appear in the International Workshop on Quality of Service (IWQoS) 2002.

Papers accepted for publication:

- A Measurement-Based Analysis of the Real-Time Performance of the Linux Kernel," Luca Abeni, Ashvin Goel, Buck Krasic, Jim Snow, and Jonathan Walpole, to appear in Proceedings of The 8th IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS 2002), San Jose, California, September 2002.

Papers submitted:

- "Supporting Time-Sensitive Applications on General-Purpose Operating Systems," Ashvin Goel, Luca Abeni, Jim Snow, Charles Krasic, Jonathan Walpole, in submission to OSDI 2002 (submitted May 2002).

5.2.9 02Q3

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts. A paper has been accepted for publication:

- Infopipes: An Abstraction for Multimedia Streaming, by Andrew Black, Rainer Koster, Jie Huang, Jonathan Walpole, and Calton Pu, to appear in *Multimedia Systems Journal*, ACM Press and Springer Verlag.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload.

Papers accepted for publication:

- Thread Transparency in Information Flow Middleware, by Rainer Koster, Andrew Black, Jie Huang, Jonathan Walpole, Calton Pu. To appear in Software-Practice and Experience, 3:1-2, 2003.
- Supporting Time-Sensitive Applications on General-Purpose Operating Systems, by Ashvin Goel, Luca Abeni, Jim Snow, Charles Krasic, Jonathan Walpole. To appear in the Proceedings OSDI 2002, December 2002.
- Analysis of a Reservation-Based Feedback Scheduler, by Luca Abeni, Luigi Palopoli, Guiseppe Lipari and Jonathan Walpole, in Proceedings of the Real Time

Systems Symposium (RTSS 2002), Austin, Texas, December 2002.

Papers presented in this Quarter:

- A Measurement-Based Analysis of the Real-Time Performance of the Linux Kernel," Luca Abeni, Ashvin Goel, Buck Krasic, Jim Snow, and Jonathan Walpole, to appear in Proceedings of The 8th IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS 2002), San Jose, California, September 2002.

Papers submitted:

- Quality-Adaptive Media Streaming by Priority Drop, by Charles Krasic and Jonathan Walpole. Submitted to the 23rd International Conference on Distributed Computing Systems, (ICDCS 2003), Providence, Rhode Island, May 19-22, 2003. Submitted September 2002.

- NetVCR: A High-Performance Packet Replay Engine," Wu-chang Feng, Abdelmajid Bezzaz, by Wu-chi Feng, Jonathan Walpole. Submitted to the 4th USENIX Symposium on Internet Technologies and Systems, Seattle, Washington, March 2003; submitted September 2002.

- Using Dynamic Optimization for Control of Real Rate Network and CPU Resource Management Applications, by Varin Vahia, Ashvin Goel, Molly H. Shor, Jonathan Walpole, and David Steere. Submitted to ACC 2002, submitted September 2002.

5.2.10 02Q4

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts. A paper was published in 02Q4:

- Infopipes: An Abstraction for Multimedia Streaming, by Andrew Black, Rainer Koster, Jie Huang, Jonathan Walpole, and Calton Pu, in *Multimedia Systems Journal*, 8(5): pp 406-419 (2002), ACM Press and Springer-Verlag.

Real-Rate Infopipes. Our work has been primarily in the Kernel Layer, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload.

Two papers have been published in 02Q4 and one paper is awaiting publication:

- Thread Transparency in Information Flow Middleware, by Rainer Koster, Andrew Black, Jie Huang, Jonathan Walpole, Calton Pu. To appear in Software-Practice and Experience, 3:1-2, 2003.

- Supporting Time-Sensitive Applications on General-Purpose Operating Systems, by Ashvin Goel, Luca Abeni, Jim Snow, Charles Krasic, Jonathan Walpole. To appear in the Proceedings OSDI 2002, December 2002.
- Analysis of a Reservation-Based Feedback Scheduler, by Luca Abeni, Luigi Palopoli, Guiseppe Lipari and Jonathan Walpole, in Proceedings of the Real Time Systems Symposium (RTSS 2002), Austin, Texas, December 2002.

Two PhD theses (partially supported by this contract) have been defended at OGI during 02Q4. Prof. J. Walpole was their advisor. Prof. C. Pu served on the committee for both theses.
- "Operating System Support for Low-Latency Streaming", Ashvin Goel, Ph.D Thesis, Oregon Graduate Institute, November 2002.
- "Modeling the Bandwidth Sharing Behavior of Congestion Controlled Flows", Kang Li, Ph.D Thesis, Oregon Graduate Institute, November 2002.

New papers that were submitted for publication:
- "Under the Plastic: A Quantitative Look at DVD Video Encoding and Its Impact on Video Modeling," Wu-chi Feng, Jin Choi, Wu-chang Feng and Jonathan Walpole, in submission to Packet Video 2003 (PV2003), Nantes, France, April 2003.
- "Adaptive Live Video Streaming by Priority Drop," Jie Huang, Charles Krasic, and Jonathan Walpole, in submission to the IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS 2003), Miami, Florida, July 2003.
- "System Support for High-Performance Application Overlays," Charles Krasic, Ashvin Goel, Ludovic Martorell, Jonathan Walpole, Wu-chi Feng, Wu-chang Feng, in submission to the 13th International Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV 2003), Monterey, California, June 2003.
- "Quality-Adaptive Media Streaming by Priority Drop," Charles Krasic, Jonathan Walpole, Wu-chi Feng, in submission to the 13th International Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV 2003), Monterey, California, June 2003.

5.2.11 03Q1

Infopipe Abstractions. We continued to develop the Infopipe abstractions through conceptual refinement and prototyping. This is in parallel to and complementing other Infopipe software development efforts.

Real-Rate Infopipes. Our work has been primarily in the kernel and middleware layers, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive

resource management software that preserve QoS and have graceful degradation during overload.

One journal paper is awaiting publication:

- Thread Transparency in Information Flow Middleware, by Rainer Koster, Andrew Black, Jie Huang, Jonathan Walpole, Calton Pu. To appear in Software-Practice and Experience, 3:1-2, 2003.

Four papers were accepted for publication:

- "Under the Plastic: A Quantitative Look at DVD Video Encoding and Its Impact on Video Modeling," Wu-chi Feng, Jin Choi, Wu-chang Feng and Jonathan Walpole, in submission to Packet Video 2003 (PV2003), Nantes, France, April 2003.

- "Adaptive Live Video Streaming by Priority Drop," Jie Huang, Charles Krasic, and Jonathan Walpole, in Proceedings of the IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS 2003), Miami, Florida, July 2003.

- "Adaptive Live Video Streaming by Priority Drop," Jie Huang, Charles Krasic, and Jonathan Walpole, a poster in the Proceedings of Packet Video 2003 (PV2003), Nantes, France, April 2003.

- "Quality-Adaptive Media Streaming by Priority Drop," Charles Krasic, Jonathan Walpole, Wu-chi Feng, in submission to the 13th International Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV 2003), Monterey, California, June 2003.

Paper submitted in 03Q1:

- "Education that Integrates Computer Science and Control Engineering," Bonnie Heck, Molly Shor, and Jonathan Walpole, in submission to IEEE Conference on Decision and Control (CDC2003)- invited session on education, submitted March 2003.

- "Using Dynamic Optimization for Control of Real Rate CPU Resource Management Applications," Varin Vahia, Ashvin Goel, Jonathan Walpole, and Molly Shor, in submission to IEEE Conference on Decision and Control (CDC2003), submitted March 2003.

5.2.12 03Q3

Real-Rate Infopipes. Our work has been primarily in the kernel and middleware layers, divided into two areas. The first area is the research on Real-Rate Infopipes, with the current focus on the smooth streaming of QoS data that share the same network with TCP. We are building an adaptive real-rate Infopipe network component that composes timing properties with graceful degradation properties during overload. This incorporates some of our previous results on TCP-friendly QoS-preserving protocols. We are continuing our research efforts in applying control systems techniques to adaptive resource management software that preserve QoS and have graceful degradation during overload. Prof. Jonathan Walpole is graduating two more PhD students (Ashvin Goel and C. "Buck" Krasic) who received partial support from DARPA, including this project.

Three papers were published in 03Q3:

- "Environmental Observation and Forecasting Systems: Vision, Challenges and Successes of a Prototype," A. Baptista, T. Leen, Y. Zhang, A. Chawla, D. Maier, W-Chi Feng, Wu-Chang Feng, J. Walpole, C. Silva and J. Freire, *in Proceedings of the International Society for Environmental Information Sciences Annual Conference (ISEIS'2003) on Systems Science and Information Technology for Environmental Applications,* Regina, Sask, Canada, July, 2003.

- "Adaptive Live Video Streaming by Priority Drop," Jie Huang, Charles Krasic, and Jonathan Walpole, *in Proceedings of the IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS 2003),* Miami, Florida, July 2003.

- "TCPivo: A High-Performance Packet Replay Engine," Wu-chang Feng, Ashvin Goel, Abdelmajid Bezzaz, Wu-chi Feng, Jonathan Walpole, *in Proceedings of the SIGCOMM Workshop on Models, Methods and Tools for Reproducible Network Research (MoMeTools),* Karlsruhe, Germany, August 2003.

5.2.13 03Q4

With the budget constraints on the project, the OGI subcontract is being terminated for FY04. The main effort is to transition the project personnel to other projects and complete the ongoing research relevant to Embedded Infopipes. Two papers were published in 03Q4:

- "Education that Integrates Computer Science and Control Engineering," by Bonnie Heck, Molly Shor, and Jonathan Walpole, *in Proceedings of the 42nd IEEE Conference on Decision and Control, invited session on education,* Maui, Hawaii, December 9-12, 2003.

- "Using Dynamic Optimization for Control of Real Rate CPU Resource Management Applications," by Varin Vahia, Ashvin Goel, Jonathan Walpole, and Molly Shor *in Proceedings of the 42nd IEEE Conference on Decision and Control (CDC2003),* Hawaii, December 9-12, 2003.

5.3   Collaboration with BBN OEP

5.3.1   02Q2

Multi-UAV Demo. The GT team has successfully demonstrated the Embedded Infopipe using PBIO and ECho software as well as its integration with the BBN OEP at the April PI Meeting. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. This is informally known as the "Source-Based Filtering" capability in the BBN Multi-UAV demo. Further integration with the BBN OEP has been proposed.

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program) on the modeling and verification of information

flows in the context of reactive programming. The threads package outlined in the previous section, for example, supports a reactive programming model that can be integrated with Timber concepts and software. In addition, the OGI team has been adapting a wireless video source mounted on a robot car (originally developed under the Quorum program) for integration with the BBN demo.

5.3.2 02Q3

Multi-UAV Demo. The GT team has successfully demonstrated the Embedded Infopipe using PBIO and ECho software as well as its integration with the BBN OEP at the April PI Meeting. The demo consists of several laptops representing information sources and sinks. They communicate through a shared and limited wireless environment. The sources use cameras to simulate UAVs generating real-time video feeds. The sink (simulating commander's desk) chooses the resolution and frame rate of interesting sources. The system controls and adapts the network bandwidth allocation according to the commander's choices. This is informally known as the "Source-Based Filtering" capability in the BBN Multi-UAV demo. We have discussed some of the new Infopipe capabilities with BBN are planning the integration with the BBN OEP for either the December PI Meeting or the next PI meeting in Spring 2003.

5.3.3 02Q4

Multi-UAV Demo. We are developing the next generation Infopipe software tools, which will demonstrated in the next PCES PI Meeting as the Infopipe Version of the Multi-UAV demo. We are discussing with BBN OEP team the potential integration of this version of demo into the OEP mainline.

5.3.4 03Q1

Collaboration. At OGI (Jonathan Walpole), we have been working with the Timber project (also funded by PCES program) on the modeling and verification of information flows in the context of reactive programming. The threads package outlined in the previous section, for example, supports a reactive programming model that can be integrated with Timber concepts and software. In addition, the OGI team has been adapting a wireless video source mounted on a robot car (originally developed under the Quorum program) for integration with the BBN demo. Our modular development approach based on Infopipes match well with the expected merger of BBN and Boeing OEPs in the PCES II program.

5.3.5 03Q3

Multi-UAV Demo. The latest version of the Infopipe software helps to build the latest version of the demo. The demo was successfully demonstrated at the PI meeting.

The demonstration uses TAO software as the middleware in its building block. BBN's OEP is built on top of ACE+TAO too. This can lead to the next step integration with the BBN OEP. The demo introduces additional type of the video source to OEP. The demo also introduces more layers for the adaptation. The OEP used to only transmit MPEG video stream. The GT team has once built a system to simulate UAVs using PBIO and the source-based filtering. We plan to work with BBN together to come up a meaningful integration of the latest Infopipe technology and the existing OEP.

Newly introduced data stream can help BBN to test its OEP testbed.

5.3.6 03Q4

Multi-UAV Demo. In October 2003, two members of the GT team (Galen Swint and Wenchang Yan) visited BBN. During the meeting, a newly developed demo was presented. The demo combined the latest technology from both sides, the Infopipe QoS filters and the BBN OEP. The system consisted of different components. But the two major parts were the video producer and the video consumer. The video producer had the functionality inherited from the Infopipe SenderPipe and the OEP Sender. On the other side, the video consumer inherited functionality provided by the OEP Receiver and the Infopipe ReceiverPipe. The integration introduced more features into the OEP.

During the meeting, Gary (BBN) also updated us the latest progress in OEP. We also discussed the next step in our technology integration. The new direction of the Infopipe is to design a system to communicate with BBN's OEP. The QoS adaptation mechanism used in Infopipes can be added into the existing OEP QoS management scheme. The GT team is working on the parts that can accomplish this.

5.3.7 04Q1

Multi-UAV Demo. The new demo shows the successful integration of the OEP and the Infopipe technology. The GT team is still working on a project to move some of the Infopipe QoS management mechanisms into OEP. This could introduce new dimension of the application level QoS management in OEP.

The GT team is working on the report based on the approach. The GT team plan to send the report to BBN. The difficulty of the new collaboration includes the QuO qosket representation of the Infopipe QoS management scheme. The BBN side will help the GT team in this work.

5.3.8 04Q2

Multi-UAV Demo. The GT team has packaged the Optimized Compression Rate mechanism into a qosket. The qosket includes the QuO SysConds specifically created for the system measurement. We have tested the management scheme in our UAV system. Since qosket provides us a clean interface for plugging different pieces of technology into OEP, it can be ported into the current OEP easily. Integration efforts have been made with BBN, but finally we couldn't make it to the last step due to the budget cut.

6 Artifacts Developed

6.1 Artifacts Published by Georgia Tech

6.1.1 00Q3 through 00Q4

From the Continual Queries project (GT), two services were released for public use in May: the XWRAP Elite wrapper development tools and the WebCQ update monitoring tools. These software tools and services will be used and included in the Infopipe toolkit (Application Level). These services are accessible through Prof. Ling Liu's web page: http://www.cc.gatech.edu/~lingliu.

The Context-Aware Toolkit supports the rapid development of distributed applications that know about the environment. It is being used for the development of applications in the GT Aware Home project. The toolkit is available for download at <http://www.cc.gatech.edu/fce/ctk>.

6.1.2 01Q1 through 01Q2

The Infosphere project at GT is successor to several other DARPA-funded grants and contracts that have resulted in significant software publications such as Continual Queries, PBIO, and ECho. There have been no new published artifacts in this quarter.

6.1.3 01Q3

The Infosphere project at GT is successor to several other DARPA-funded grants and contracts that have resulted in significant software publications such as Continual Queries, PBIO, and ECho. We are working on the multi-UAV demo in cooperation with BBN. There have been no new published artifacts in this quarter.

6.1.4 01Q4

The Infosphere project at GT is successor to several other DARPA-funded grants and contracts that have resulted in significant software publications such as Continual Queries, PBIO, and ECho. We are working on the multi-UAV demo in cooperation with BBN. Several software tools related to Middleware Infopipes have been made available internally to GT: XMIT (XML Metadata Integration Toolkit), PDS (Proactive Directory Service), and AVS (Active Video Streams) demonstration software.

6.1.5 02Q1

No new artifacts were published.

6.1.6 02Q2 through 02Q3

We have completed the first version of the multi-UAV demo in cooperation with BBN. Several software tools related to Middleware Infopipes have been made available internally to GT, specifically the SIP/XIP version of Infopipe software tools. We are discussing collaboration with several universities for beta-testing and evaluation. Further integration with the BBN OEP has been proposed.

6.1.7 02Q4 through 03Q1

We are discussing collaboration with several universities for beta-testing and evaluation. We are building the Infopipe Version of the Multi-UAV Demo and the next generation

Infopipe software toolkit. The Infopipe software toolkit will be wrapped for public release after the next PCES PI Meeting.

6.1.8   03Q3

We have built our latest demonstration with the improved Infopipe software tools. The new version of the ISG code generator has been made available through the CVS download. Now it can supports more API bindings like the CORBA (TAO AVStreams). The feedback system in the Infopipe software becomes a separate component. We are in the process of testing and wrapping up the software. The first release of the Infopipe Software Toolkit will be available soon.

6.1.9   03Q4

The first official version of the Infopipe software has been put into the public domain. The necessary documents are also made possible with the package. Along with the software tools, some simple examples can be used to get the user started using the Infopipe software.

6.1.10 04Q1

The Ptolemy tool has been made available internally to other GaTech groups. The latest "Multi-UAV demo" has been developed using ACE+TAO middleware and BBN's QuO.

6.1.11 04Q2

The 0.9 release of the Infopipe Software Toolkit is available for download now. The toolkit reflects the latest progress in the project. The Optimized Compression Rate Qosket has been delivered to BBN. Components made into the current Infopipe software release have been tested extensively.

6.2   Artifacts Published by OGI

6.2.1   00Q3 through 00Q4

There have been no new published artifacts since the Quorum demo and technology transfer meeting in Washington (02/00).

6.2.2   01Q1 through 01Q2

The Infosphere project at OGI is successor to several other DARPA-funded grants and contracts that have resulted in significant software publications such as Synthetix and Quasar. There have been no new published artifacts since the Quorum demo and technology transfer meeting in Washington (02/00) and the HiPer-D 2000 demo. Incremental software components being published (on the web http://www.cse.ogi.edu/~kangli/) include some interesting MATLAB-based simulations for the bandwidth sharing among TCP flows.

6.2.3   01Q3

- We released a public domain version of the software oscilloscope (Gscope - A Software Oscilloscope Library for Linux) so that it can be used separately from the Quasar pipeline. This software, together with documentation and some examples is available at the following URL: http://gscope.sourceforge.net/.

- We also completed and demonstrated a new and much improved version of the Quasar pipeline based on "priority progress streaming." This version does real-time video streaming over TCP-based unicast networks. The code has been completed and packaged, but has not been released to the public because we are finalizing the wording of the licensing agreement with OHSU. We want to make it freely available for non-commercial use, but retain the ability to license it for a fee for commercial use. We are also beginning the process of filing for patents.

6.2.4 01Q4

- We have been working on producing a live-source version of our quality adaptive video streaming pipeline for the BBN UAV demo (in the PCES program). We have a working version on desktop machines. We are enhancing it to run over wireless links on notebook computers and eventually on the OGI robot. Our plans are to integrate it with the BBN software, using our pipeline for fine-grain, high frequency video adaptations and BBN QUO explicit events to trigger coarse-grain, infrequent resolution adaptations at the video source. We also plan to integrate it with the Timber code that is doing real-time control of the robot.

6.2.5 02Q1

No new artifacts were published.

6.2.6 02Q2 through 02Q3

- We have been working on producing a live-source version of our quality adaptive video streaming pipeline for the BBN UAV demo (in the PCES program). We have a working version on desktop machines. We are enhancing it to run over wireless links on notebook computers and eventually on the OGI robot. Our plans are to integrate it with the BBN software, using our pipeline for fine-grain, high frequency video adaptations and BBN QUO explicit events to trigger coarse-grain, infrequent resolution adaptations at the video source. We also plan to integrate it with the Timber code that is doing real-time control of the robot. Most of this software will be demonstrated in the July PCES PI Meeting.

6.2.7 02Q4 through 03Q1

- We have been working on producing a live-source version of our quality adaptive video streaming pipeline for the BBN UAV demo (in the PCES program). We have a working version on desktop machines. We are enhancing it to run over wireless links on notebook computers and eventually on the OGI robot. Our plans are to integrate it with the BBN software, using our pipeline for fine-grain, high frequency video adaptations and BBN QUO explicit events to trigger coarse-grain, infrequent resolution adaptations at the video source. We also plan to integrate it with the Timber code that is doing real-time control of the robot.

7 Completed Travel

7.1 00Q3

Invited talks and collaboration activities on the Infosphere project during 00Q3. Unless otherwise stated, the talks and travel have been done by the PI (Prof. Pu).

1. 07/03/00 Osaka University, Japan, ``Infosphere: Smart Delivery of Fresh Information'', Host: Prof. Shojiro Nishio. This meeting is part of the effort to develop collaboration activities between the Infosphere project and Japanese researchers. Dr. Pu discussed research opportunities with several faculty members, researchers, and graduate students at the Osaka University.

2. 07/04/00 Kyoto University, Japan, ``Infosphere: Smart Delivery of Fresh Information'', Host: Prof. Kambayashi. This meeting is part of the effort to develop collaboration activities between the Infosphere project and Japanese researchers. Dr. Pu discussed research opportunities with several faculty members, researchers, and graduate students at the Kyoto University.

3. 07/05/00 SIGMOD Japan annual conference, ``Recent Research Results from Infosphere'', Host: Prof. Masaru Kitsuregawa. This meeting is part of the effort to develop collaboration activities between the Infosphere project and Japanese researchers. The meeting was well attended by Japanese researchers from the information technology industry.

4. 07/06/00 Mitsubishi Research Institute, Tokyo, ``Pervasive Is The Computer'', Host: Mr. K. Miyazaki. This meeting is part of the effort to develop collaboration activities between the Infosphere project and Japanese researchers. This meeting was well attended by researchers from the Mitsubishi group of industries such as Mitsubishi Electric and Mitsubishi Auto Industries.

5. 07/26/00, IBM T.J. Watson Research Center, New York, ``Infosphere: Smart Delivery of Fresh Information'', Host: Dr. Hui Lei. This visit was part of the effort by IBM Watson to establish collaboration with the Expedition projects.

6. 08/01/00, PCES PI Meeting, Albuquerque, ``I/O-Intensive Embedded Systems: The Infopipe Approach'', PM: Helen Gill. This is the initial PI meeting for the PCES program and the introduction of the Embedded Infopipe project.

7. 09/06/00, ``Infosphere: Smart Delivery of Fresh Information'', opening Keynote Address of the *Fifth IFCIS International Conference on Cooperative Information Systems* (COOPIS), Eilat, Israel. COOPIS is the major international conference in the area of cooperative distributed systems.

8. 10/02/00, ``Infosphere: Smart Delivery of Fresh Information'', opening Keynote Address of the *XV Brazilian Symposium on Database Systems* (SBBD), Joao Pessoa, Brazil. SBBD is the major database conference in Latin America.

9. 10/30/00, Ubiquitous Computing Workshop (DARPA/ITO PI Meeting), ``Recent Research Results from Infosphere'', PM: Jean Scholtz. This is the PI meeting for the Ubiquitous Computing seed program.

10. 12/14/00, Quorum PI Meeting (DARPA/ITO), ``Recent Results from Quasar'', PM: Gary Koob.

Meetings related to the DARPA programs directly relevant to the Infosphere and Embedded Infopipe projects.

- 08/01/00, PCES PI Meeting, Albuquerque, ``I/O-Intensive Embedded Systems: The Infopipe Approach'', PM: Helen Gill. This is the initial PI meeting for the PCES program and the introduction of the Embedded Infopipe project.

- 10/30/00, Ubiquitous Computing Workshop (DARPA/ITO PI Meeting), ``Recent Research Results from Infosphere'', PM: Jean Scholtz. This is the PI meeting for the Ubiquitous Computing seed program. From the Infosphere project, attended Calton Pu, Gregory Abowd, and Karsten Schwan of GT, plus Ashwin Goel and Jonathan Walpole of OGI.

- 12/14/00, Quorum PI Meeting (DARPA/ITO), ``Recent Results from Quasar'', PM: Gary Koob.

7.2   00Q4

Invited talks and collaboration activities on the Infosphere project during 00Q4.

11. 9/27-10/1/2000, Gregory Abowd and Anind Dey attended HUC 2000 conference in Bristol, UK. Presented CybreMinder paper listed in 00Q3 report.

12. 10/02/00, Calton Pu gave the presentation ``Infosphere: Smart Delivery of Fresh Information'', opening Keynote Address of the *XV Brazilian Symposium on Database Systems* (SBBD), Joao Pessoa, Brazil. SBBD is the major database conference in Latin America.

13. 10/30/00, Calton Pu gave the presentation ``Recent Research Results from Infosphere'' at the Ubiquitous Computing Workshop (DARPA/ITO PI Meeting), PM: Jean Scholtz. This is the PI meeting for the Ubiquitous Computing seed program. Pittsburgh, USA.

14. 11/13-16/2000, Gregory Abowd delivered keynote address at Kyoto International Conference on Digital Libraries. Also presented technical talks on ubiquitous computing research in automated capture, context-awareness and error correction to NEC Labs, the ATR Labs and Sony CSL (Tokyo) during this trip.

15. 12/11/2000, Gregory Abowd delivered the presentation, "Designing and Building Living Laboratories for Ubiquitous Computing Research: Opportunities for Software Engineering Research." Keynote address for Promodis (Programming of Modular and Distributed Systems) Swedish National conference, Gothenberg, Sweden, December 11, 2000. Also visited the PLAY Group within the Interactive Institute in Gothenberg.

16. 12/12-15/00, Shor, Steere and McNamee traveled to Sydney, Australia, to present their papers and run their special session at the 39th IEEE Conference on Decision and Control. This foreign travel was supported using external funds and was not charged to the Infosphere grant.

17. 12/14/00, Calton Pu gave the presentation ``Recent Results from Quasar'' at the Quorum PI Meeting (DARPA/ITO), PM: Gary Koob, Orlando, Florida.

Meetings related to the DARPA programs directly relevant to the Infosphere and Embedded Infopipe projects.

- 08/01/00, PCES PI Meeting, Albuquerque, ``I/O-Intensive Embedded Systems: The Infopipe Approach'', PM: Helen Gill. This is the initial PI meeting for the PCES program and the introduction of the Embedded Infopipe project.
- 10/30/00, Ubiquitous Computing Workshop (DARPA/ITO PI Meeting), ``Recent Research Results from Infosphere'', PM: Jean Scholtz. This is the PI meeting for the Ubiquitous Computing seed program. From the Infosphere project, attended Calton Pu, Gregory Abowd, and Karsten Schwan of GT, plus Ashwin Goel and Jonathan Walpole of OGI.
- 12/14/00, Quorum PI Meeting (DARPA/ITO), ``Recent Results from Quasar'', PM: Gary Koob.

Shor and Steere co-organized an invited session at the premier control theory conference in 2000 to help initiate new collaborative research between the control system and computer system research communities:

- "Challenges in The Application of Control to Computer Systems," Molly Shor (organizer), David Steere (co-organizer), Invited Session, 39th IEEE Conference on Decision and Control, Sydney, Australia, December 12-15, 2000.

Shor and Steere also proposed an invited session (currently under review) for the 2001 American Control Conference to bring together control and computer system researchers working on computer system and computer network design issues, and to include more researchers from both communities in discussions.

7.3   01Q1

Invited talks and collaboration activities on the Infosphere project during 01Q1.

1. 03/10/01 Data Engineering Workshop, Shizuoka, Japan. ``System Support for Information-Driven Applications'', Host: Prof. Masatoshi Arikawa, Univ. Tokyo, invited talk.

Meetings related to the DARPA programs directly relevant to the Infosphere and Embedded Infopipe projects.

- 02/07/01 DARPA/ITO PCES PI Meeting, San Diego. ``Embedded Infopipes Project'', Host: Dr. Douglas Schmidt.

7.4   01Q2

Invited talks and collaboration activities on the Infosphere project during 01Q2.

- 03/10/01 Data Engineering Workshop, Shizuoka, Japan. ``System Support for Information-Driven Applications'', Host: Prof. Masatoshi Arikawa, Univ. Tokyo, invited talk.
- 04/11-13 Visit of Charles Consel to Georgia Institute of Technology to work on the Embedded Infopipes project.

Meetings related to the DARPA programs directly relevant to the Infosphere and Embedded Infopipe projects.

- 02/07/01 DARPA/ITO PCES PI Meeting, San Diego. ``Embedded Infopipes Project'', Host: Dr. Douglas Schmidt.

7.5 01Q4

Invited talks and collaboration activities on the Infosphere project during 01Q3.

The OGI personnel gave talks at University of Bordeaux, France, University of Oslo, Norway, and at the International Workshop on Interactive Distributed Multimedia Systems in the United Kingdom. The travel expenses for these trips was funded from other sources.

Calton Pu gave the following talks during 01Q3:

1. 07/04/01 EPFL, Lausanne, Switzerland. ``Infosphere: Smart Delivery of Fresh Information'', Host: Prof. Karl Aberer.
2. 07/10/01 Lawrence Berkeley Labs, California. ``XwrapElite: toolkit'', DoE Data Management center kick-off meeting, Host: Dr. Arie Shoshani.
3. 08/29/01 National Taiwan University, Taiwan. ``Infosphere: Smart Delivery of Fresh Information'', Host: Prof. Ming-syan Chen.
4. September 8-11, attended a Dagstuhl seminar on Ubiquitous Computing in Dagstuhl, Germany.

7.6 01Q4

Invited talks and collaboration activities on the Infosphere project during 01Q4.

The OGI personnel gave talks at University of Bordeaux, France, University of Oslo, Norway, and at the International Workshop on Interactive Distributed Multimedia Systems in the United Kingdom. The travel expenses for these trips was funded from other sources.

Calton Pu gave the following talks during 01Q4:
5. 10/01/01 Institute of Industrial Sciences, University of Tokyo, Japan. ``Web Information: So Near and Yet So Far''.
6. 10/24/01 PCES PI Meeting, Phoenix. ``Recent Updates on Embedded Infopipes'', PM: Douglas Schmidt.
7. 11/16/01 University of Georgia. ``Infosphere: Smart Delivery of Fresh Information'', Host: Prof. Amit Sheth.

7.7 02Q1

Invited talks and collaboration activities on the Infosphere project during 02Q1.

The OGI personnel gave talks at University of Bordeaux, France, University of Oslo, Norway, and at the International Workshop on Interactive Distributed Multimedia Systems in the United Kingdom. The travel expenses for these trips was funded from other sources.

Project members gave the following talks during 02Q1:
8. 1/22-23/02 Ubiquitous Computing PI Meeting, Washington. Calton Pu gave a talk on ``Recent Updates on Infosphere'', PM: Gary Koob. Other Infosphere speakers include: Karsten Schwan of Georgia Institute of Technology and Wu-chi Feng of Oregon Graduate Institute. Wu-chang Feng of Oregon Graduate Institute also attended the meeting.
9. 02/18/02 MSREC Seminar, Georgia Tech. Calton Pu gave a talk on ``Infosphere: Smart Delivery of Fresh Information'', Host: Prof. Richard Fujimoto.

10. February 2002. Jonathan Walpole gave the talk "Systems Support for Next Generation Streaming Applications" at: University of Oslo, Norway, and University of Tromso, Norway.

7.8 02Q2

Invited talks and collaboration activities on the Embedded Infopipes project during 02Q2.

The travel expenses for international trips were funded from other sources.

Project members gave the following talks during 02Q2:

11. 04/03/02 DARPA/ITO PCES PI Meeting, San Diego. "Update Embedded Infopipes Project", by Prof. Pu.
12. 04/07/02 Yamacraw Distinguished Lecture, Savannah State University, "Infosphere: Smart Delivery of Fresh Information", by Prof. Pu. Host: Prof. Raymond Greenlaw, Armstrong Atlantic State University.

7.9 02Q3

Invited talks and collaboration activities on the Embedded Infopipes project during 02Q2.

The travel expenses for international trips were funded from other sources.

Project members gave the following talks during 02Q2:

13. 07/11/02 DARPA/IXO PCES PI Meeting, Portland, Oregon. "Update on Embedded Infopipes Project", by Prof. Pu.
14. 09/23/02 2002 SIGOPS European Workshop, St. Emilion, France. Invited panel presentation, "Is Operating Systems Research Worthwhile, or Is Worthwhile Research Operating Systems?" by Prof. Pu. Panel organizer: Prof. Henry Levy.
15. 09/27/02 Department Colloquium, University of Tromso, Norway. "Infosphere: Smart Delivery of Fresh Information", by Prof. Pu. Host: Prof. Weihai Yu.

7.10 02Q4

Invited talks and collaboration activities on the Embedded Infopipes project. (The travel expenses for international trips were funded from other sources.)

Project members gave the following talks during 02Q4:

16. 10/18/02 Department Colloquium, University of Osaka, Japan. "Internet Data Management Research at CERCS", Host: Prof. Shojiro Nishio, Dean of School of Informatics, University of Osaka.
17. 12/03/02 DARPA/IXO PCES PI Meeting, Austin, Texas. "Update on Embedded Infopipes Project", Host: Dr. Douglas Schmidt.

7.11 03Q1

Invited talks and collaboration activities on the Embedded Infopipes project. (The travel expenses for international trips were funded from other sources.)

Prof. Calton Pu gave the following talks during 03Q1:

1. 02/03/03, Department Colloquium, Institute of Mathematics, Statistics, and Computing, University of Sao Paulo, "Continual Queries: Intelligent Access to Fresh Information". Host: Prof. Joao Ferreira.

2. 02/05/03, Department Colloquium, Institute of Computing, University of Campinas, "Continual Queries: Intelligent Access to Fresh Information". Host: Prof. Ricardo Anido.

7.12 03Q3

Invited talks and collaboration activities on the Embedded Infopipes project. (The travel expenses for international trips were funded from other sources.)

Prof. Calton Pu gave the following talks during 03Q2 and 03Q3:
1. 06/25/03, Department Colloquium, Nara Advanced Institute of Science and Technology, "Continual Queries: Intelligent Access to Fresh Information". Host: Prof. Shunsuke Uemura.
2. 07/09/03, Department Colloquium, Kyoto University, "Infosphere: Smart Delivery of Fresh Information". Host: Prof. Yahiko Kambayashi.
3. 07/14/03, Department Colloquium, Tokyo Institute of Technology, "Infosphere: Smart Delivery of Fresh Information". Host: Prof. Shigeru Chiba.
4. 07/17/03, Association Colloquium, Mitsubishi Computer and Communications Research Association (Mitsibuishi Research Institute). "Ubiquitous Data Processing". Host: Mr. Seiichi Miyazaki.
5. 07/24/03, DoCoMo YRP Research and Development Center, "Infosphere: Smart Delivery of Fresh Information". Host: Mr. Michio Miki.
6. 07/25/03, University of Tsukuba, Department Colloquium. "Continual Queries: Intelligent Access to Fresh Information". Host: Prof. Hiroyuki Kitagawa.
7. 08/29/03, HP Labs, "Infosphere: Smart Delivery of Fresh Information". Host: Mr. John Sontag and Dr. Mat Hans.
8. 09/22/03, FHG/IPSI, Darmstadt, Germany, informal talk on Infosphere. Host: Dr. Erich Neuhold.
9. 09/26/03, Technical University of Dresden, Germany, informal talk on Infosphere. Host: Prof. Hermann Haertig.

7.13 03Q4

Invited talks and collaboration activities on the Embedded Infopipes project. (The travel expenses for international trips were funded from other sources.)

Prof. Calton Pu gave the following talks during 03Q4:
3. 11/26/03, Pontifical Catholic University of Rio Grande do Sul (PUCRS), Porto Alegre, Brazil, "Infosphere: A Midterm Update on Infopipes". Host: Prof. Duncan Ruiz.
4. 11/28/03, University of Sao Paulo, Sao Paulo, Brazil, "Infosphere: A Midterm Update on Infopipes". Host: Prof. Fabio Kon and Joao Eduardo Ferreira.
5. 12/01/03, University of Campinas, Campinas, Brazil, informal talk on Infosphere. Host: Prof. Claudia Medeiros.
6. 12/03/03, IBM Almaden Research Center, "Infosphere: A Midterm Update on Infopipes". Host: Dr. David Chambliss.

7.14 04Q1

Invited talks and collaboration activities on the Embedded Infopipes project. (The travel expenses for international trips were funded from other sources.)

Prof. Calton Pu gave the following talks during 03Q4:

7. 01/26/04, IBM Tokyo Research Lab, "Infosphere: A Midterm Update on Infopipes". Host: Dr. Kazuo Iwano.
8. 01/27/04, University of Tokyo, Institute of Industrial Sciences , "Infosphere: A Midterm Update on Infopipes". Host: Prof. Masaru Kitsuregawa.
9. 03/17/04, Institute of Computer Science, Foundation for Research and Technology – Hellas (ICS/FORTH), Heraklion, Crete, Greece, "Infosphere: A Midterm Update on Infopipes". Host: Prof. Evangelos Markatos.

7.15 04Q2

Invited talks and collaboration activities on the Embedded Infopipes project. (The travel expenses for international trips were funded from other sources.)

Prof. Calton Pu gave the following talks during 03Q4:

10. 05/20/04, Corporate Technology Group, Intel, Portland, Oregon, "Infosphere: A Midterm Update on Infopipes". Host: Dr. Sridhar Iyengar.

8   Equipment Purchases and Description

No equipment has been requested or purchased using the Infosphere tasks 1 through 5 funds.

9 Summary of Activity

9.1 Work Focus

9.1.1 00Q3 through 01Q2

We have been working on the development of Infopipe software at OGI and Georgia Tech. Conceptually, we are developing the specification language for Infopipes at the application level, middleware level, and the kernel level. On the implementation side, we are building Infopipe interfaces on top of software developed from previous DARPA funding, including the Continual Queries project, the Event Channel work in the RT-ARM project, and the Microfeedback and Quasar projects.

9.1.2 01Q3 through 02Q1

We have been working on the development of Infopipe software at OGI and Georgia Tech. Conceptually, we are developing the specification language for Infopipes at the application level, middleware level, and the kernel level. On the implementation side, we are building Infopipe interfaces on top of software developed from previous DARPA funding, including the Continual Queries project, the Event Channel work in the RT-ARM project, and the Microfeedback and Quasar projects. We have been working on a demo based on the BBN multi-UAV scenario for the Embedded Infopipe part of the project.

9.1.3 02Q2 through 03Q1

There are two main efforts at Georgia Institute of Technology. First, we have been developing the Infopipe software tools (see the SIP/XIP paper) and the integration of Infopipes into the BBN OEP Multi-UAV demo. Second, we have largely redirected the related efforts to other sources of funding, but we continue the collaboration with those projects.

9.1.4 03Q3

There are several efforts at Georgia Institute of Technology. We have been working on the release of the first complete version of the Infopipe Software toolkit. This summarizes our past efforts in the research on the language (ISL/XIP), the code generator (ISG). We are also working on the plans for further integration with the BBN OEP. We continue the collaboration with some other projects.

9.1.5 03Q4

There are several efforts at Georgia Institute of Technology. We released the first version of the Infopipe software. New direction of the integration with OEP has been initiated. The software release summarizes our past efforts in the research on the language (ISL/XIP), and the code generator (ISG).

9.1.6 04Q1

There are several efforts at Georgia Institute of Technology. We adopted the Berkeley's Ptolemy workflow tool in the Infopipe project. We had good results from the Emulab experiments (GQM). The Infopipe code generator is capable of supporting more communication APIs (ECho).

9.1.7   04Q2

There are several efforts at Georgia Institute of Technology. We made the new release of the Infopipe Software Toolkit. The Infopipe QoS management mechanism (OCR) has been ported to QuO language.

9.2   Significant Events

9.2.1   00Q3

The main project events during the reporting period are:

- 07/18/00 Project Mini-PI Meeting at OGI, with the PI and OGI co-PIs to discuss the project progress.
- 11/02-03/00 Project PI Meeting at Georgia Tech, with Jonathan Walpole and Ashvin Goel visiting GT to discuss collaboration and technology exchange.

9.2.2   00Q4

The main project events during the reporting period are:

- 11/02-03/00 Project PI Meeting at Georgia Tech, with Jonathan Walpole and Ashvin Goel visiting GT to discuss collaboration and technology exchange.

The main funding program events during the reporting period are:

- 10/30-11/00 Ubiquitous Computing PI Workshop at CMU, with the participation of Calton Pu (PI, with presentation), Karsten Schwan, and Gregory Abowd of Georgia Tech and Jonathan Walpole and Ashvin Goel of OGI.
- 12/14-16/00 Quorum PI Meeting in Orlando, with the attendance and presentation of Calton Pu (PI) of Georgia Tech.
- 2/6-8/01 PCES PI Meeting in San Diego, with the attendance and presentation of Calton Pu (PI) of Georgia Tech.

9.2.3   01Q1

The main funding program events during the reporting period are:

- 2/6-8/01 PCES PI Meeting in San Diego, with the attendance and presentation of Calton Pu (PI) of Georgia Tech.

9.2.4   01Q2

The main funding program events during the reporting period are:

- 2/6-8/01 PCES PI Meeting in San Diego, with the attendance and presentation of Calton Pu (PI) of Georgia Tech.

9.2.5   01Q3 through 01Q4

10/24/01 PCES PI Meeting, Phoenix, attended by the PI.

9.2.6   02Q1

01/22-23/2002. The final Ubiquitous Computing program PI meeting in Washington. Calton Pu and Karsten Schwan of Georgia Institute of Technology plus Wu-chi Feng and Wu-chang Feng of Oregon Graduate Institute attended the PI meeting as part of the Infosphere project.

9.2.7   02Q2 through 02Q4

April, 2002. The GT team has successfully demonstrated the Embedded Infopipe using PBIO and ECho software as well as its integration with the BBN OEP at the April PCES PI Meeting.

9.2.8   03Q1 through 03Q2

June, 2003. We presented a newly built "Multi-UAV Demo" during the June 2003 PI meeting. The demo was built with layers of the Infopipe filters. Part of the demo was generated by the ISG code generator. The generated code includes the code that helps the setup of the data connection. The generated code also includes the Infopipe representation of the information flow.

9.2.9   03Q3 through 04Q2

October, 2003. The GT team has come up with the idea of further incorporating the Infopipe technology with the OEP. The idea is to use QuO programming API to implement the Infopipe component. Two team members went to BBN (Boston) to meet with the OEP team and discuss this collaboration.